Comprehensive Business Modelling: Hydrogen and its Integration in the Dutch Energy System

Business modelling from the perspective of a public-private partnership for the case of 'H-vision', a project for the implementation of blue hydrogen in the Port of Rotterdam

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Business modelling from the perspective of a public-private partnership for the case of 'H-vision', a project for the implementation of blue hydrogen in the Port of Rotterdam

By

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Preface

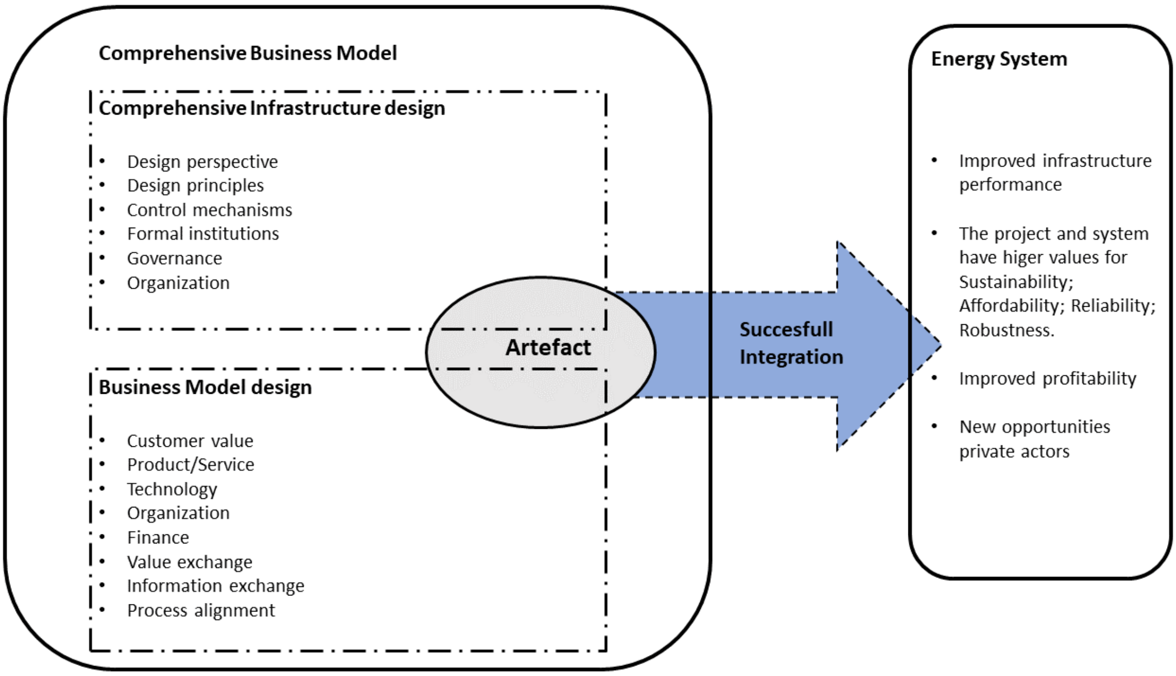
The goal of this thesis is to determine the effects of integrating blue hydrogen into the Dutch energy system. A new framework is presented to assess several different designs for the business model, infrastructure, and market. This framework is applied to the case of the H-vision project. Three business models are tested against three energy system designs. As such we can determine if which of the three combinations presents the most benefits and also which combination is the most likely to be executed. I invite everyone to read this thesis with a heuristic perspective to learn more about the hydrogen economy and the Dutch energy system. I hope it will be as educating for you as it has been for me.

Executive Summary

Around the globe countries, organizations, and people are struggling with the revision of their energy system. The process of revisioning is arduous… Energy systems are complex and rigid socio-technical systems that don't want to change. Especially since there is no concrete problem like an energy shortage that needs solving. The cause of our arduous endeavor does not lie in the present but in the future. This thesis aims to be a small part of the solution for the Dutch energy transition.

The Netherlands have set their goal to reduce carbon emissions in 2030 by 49% relative to the year 1990. This ambitious goal is to be fulfilled by increasing the amount of renewable energy sources, implementing energy saving technologies, and the use of hydrogen as an energy carrier. All actors within the energy system must transform their business models in order to maintain operations in a sustainable manner. This proves to be hard especially in sectors such as transport, industry and energy. Large capital investments accompany most changes to the energy system due to its rigid and complex nature. Often projects that deliver value, in their ability to decarbonize primary energy consumption, are not developed due to their inability to deliver satisfactory value in economics. A misplacement of benefits and rewards is present, and consequently private parties do not want to take the risk of incurring loss. To successfully achieve the goals set by the Dutch government, public parties must in some way accommodate these energy infrastructure projects. However, the involvement of public parties results indisputably to a change in the business model. Because interests and requirements for energy infrastructure projects are different for public and private parties. Thus, I argue that in order to successfully integrate energy infrastructure projects there is a need for a business model framework from the perspective of the public-private partnership. The case used in this research was that of H-vision. A project where several large industrial actors partnered to assess the viability of producing and consuming 'blue' hydrogen in the Port of Rotterdam. This project promises to decarbonize a large part of industry in the Port of Rotterdam. However, it suffers from a significant financial gap. Without a form of government support the private parties will most likely not invest in this project. The government has broader interests than pure economics and must also assess the system effects of integrating the H-vision project into the Dutch energy system. Thus, the main research question is posed as: *How does the performance of the H-vision business model change when system effects are incorporated in the design?*

To answer this question this research makes use of literature written about topics such as business models and socio-technical systems to develop the conceptual model. The conceptual model argues that the combination of a design for the business model with a design for the system will facilitate successful integration of the project into the energy system. For the analytical framework eight factors were used to assess the business model. These were: 'customer value', 'product/service', 'technology', 'organization', 'finance', 'value exchange', 'information exchange', and 'process alignment'. Six factors were used to assess the system design. Three of these: 'design perspective', 'design principles', and 'control mechanisms' were used to examine the technical infrastructure of the energy system. The other three: 'formal institutions', 'governance', and 'organization' were used to examine the social infrastructure of the energy system i.e. the market. All these factors had distinct influences on the four factors that were used to test the outcome of the system integration. These were: 'sustainability', 'affordability', 'reliability', 'robustness'. These factors were tested against expert scrutiny to determine their relevance for integrating a hydrogen related project into the energy system. This framework is called the comprehensive business model framework, presented in the figure below. It can be used by managers as a tool for the collection of data and accordingly processing the gathered information.



Comprehensive Business Modelling framework

The framework was used to assess three business models and three plausible system designs. The three business models were chiefly defined by the scale of hydrogen production and the amount of CO_2 reduction. The system designs were mainly defined by the level of engagement and commitment of the government to integrate hydrogen as an energy carrier in the Dutch energy system. The results show that there are two combinations that deliver the most value while simultaneously ensuring an equal distribution of risk and rewards. These are the: 'medium business model with the hydrogen backbone system design' and the 'maximum business model with the hydrogen economy development'. Two combinations should absolutely not be pursued: 'minimal business model with the standalone system design' and the 'maximum business model with the standalone system design'. These lead (presumably) to detrimental results relatively to the other combinations and the present configuration of the Dutch energy system.

The main findings include that the performance of H-vision does improve when including system effects in its design. The inclusion of system effects creates a clearer picture of all the activities and adjustments necessary in the value chain. As a result, all stakeholders can determine their roles and responsibilities in the H-vision project. Private partners maintain their competitiveness by implementing cost effective measures to decarbonize their activities. Public partners can actively shape the energy system in such a way that enables them to achieve their sustainability goals while reducing negative externalities. The framework is proposed as a tool to maximize the creation of value in public-private partnerships in the field of energy system transition. The H-vision project would greatly benefit from a dedicated and well-organized public-private partnership. My hope is that these findings will contribute to the successful integration of H-vision and other related hydrogen projects in the Netherlands.

Keywords: Comprehensive Business Modelling, Public-Private Partnerships, Hydrogen, System Integration.

Acknowledgements

This thesis project has been an extremely insightful and fun enterprise. It is the culmination of my Master of Science study, Management of Technology. I must admit that I was not extremely knowledgeable concerning the hydrogen economy and the Dutch energy system at the start of this undertaking. But with the help of my supervisors and interactions with experts in the field I have learned a great deal. I see this as only the start of a fruitful journey within industry and energy.

I would like to first thank my first supervisor Dr. Daniel Scholten for his patient and very helpful guidance during all phases in the development of this project. To Dr. Roland Ortt for his more than adequate fulfillment of the Chair position. To Dr. Ivo Bouwmans for his useful feedback as second supervisor. I want to thank all three of you for believing in me and my capabilities to execute a research in a subject where I had a trivial level of academic background. In the sense that I had not yet researched the Dutch energy system or the concept of a hydrogen economy. I want to thank my supervisors at Berenschot, Aart Kooiman and Bert den Ouden, for their support in finishing this research. The sheer amount of knowledge and information they have shared with me have been crucial in my analysis. Moreover, I would like to thank Berenschot for providing me with the resources and supportive environment during the research.

I cannot go on without mentioning the people who have made time in their busy lives to be interviewed and be part of this research. I hope you find this research useful in your work. I would also like to thank my clever and beautiful girlfriend Pauline Lobbezoo for picking my mind but also for being there in difficult moments. Last but not least I would like to thank my family & friends for the useful discussions we have had concerning the energy transition and the role of hydrogen therein. I am looking forward to new challenges and I shall take the wisdom yielded during this thesis project to tackle them.

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1 INTRODUCTION

In this chapter the underlying problems and knowledge gaps for this research will be introduced. The Dutch energy system and its connection to the hydrogen economy will be discussed. Next, the case will be defined, which is the H-vision project. A project that aims to fossil fuels by blue hydrogen as an energy carrier, in the existing Rotterdam chemical, refining and power operations. Then a discussion on how theoretical literature applies to this problem will be presented and followed by what the current gaps in literature are. The chapter will be concluded with the identified knowledge gaps, research objective, research questions and research methods. The purpose of this research is to find out how the performance of H-vision business models change when system effects are incorporated in their design.

1.1 THE DUTCH ENERGY SYSTEM

1.1.1 Dutch energy system in transition

The transition to renewable energy sources is at the top of European Union policy agenda. Whether for reasons of reducing CO_2 emission, air pollution, or security of energy supply, the European Union envisions renewable energy to replace fossil fuels. EU leaders adopted the 2030 climate & energy framework, which sets three targets for 2030: [1] at least a 40% cut in greenhouse gas emissions (from 1990 levels); [2] at least a 32% share for renewable energy; [3] at least 27% improvement in energy efficiency (European Commission, 2018). Additionally, the EU has set a long-term goal that by the year 2050 the total amount of greenhouse gas emissions should be reduced by 80-95% (European Commission, 2018). Member states are legally bound to adhere to this directive, but they have significant autonomy in how they achieve these targets. The national action plan for the Netherlands is based upon the premise that the transition to renewable energy sources should be affordable for citizens, business and the government. The Dutch 'energy agenda' aims to keep in line with the guidelines set by the EU and focusses on cost efficiency (Ministerie van Economische Zaken, 2016). The Dutch government as stated in their Declaration of Intent (2016), aim for a 49% CO_2 emissions reduction in 2030 versus 1990. This goal is tougher than the goal set by the EU government. First steps of action need to be made quickly. This change in both informal and formal institutions has a direct effect on the Dutch energy system. Actors within the system experience pressure to transform their activities into more sustainable ones. This presents these actors not only with new opportunities but also with various challenges. Especially since the energy system has grown to be a complex structure and the majority of investments necessary to change this system are very capital intensive. Table 1 presents the energy consumption and CO_2 emissions per sector in the Netherlands.

Sector	Energy consumption (PJ/year)		CO_2 emissions (Mton CO_2/year)
	Fossil fuels	Electricity	
Built environment	400	200	24
Transport & Mobility	476	6 (incl. hydrogen)	35
Agriculture	137	33	27 (incl. CH_4 & NO_2 in CO_2-eq)
Industry & Energy	410	123	101

Table 1. Final energy consumption and CO_2 emissions per sector in the Netherlands retrieved from (Energieonderzoek Centrum Nederland, 2017).

This table shows that the industry & energy sector is by far the largest producer of CO_2 and is thus a main candidate for decarbonization. Approximately 25% of the CO_2 emissions are due to electricity production in coal plants (van Santen, Rijlaarsdam, & van der Walle, 2019); 13% due to refineries (Römgens & Dams, 2018); 10% due to electricity production in gas plants (Energieonderzoek Centrum Nederland, 2017); and 12% due to steal production (Schwartz, 2019). A first step made by the Dutch house of representatives is to forbid electricity production through combustion of coal in the year 2030 (Rijksoverheid, 2017). The Netherlands currently has five active coal plants, with the three newest situated in the port of Rotterdam and Eemshaven. The owners of these plants will need to close the plants or find ways to adjust these plants to facilitate the use of sustainable fuels. Other industry and energy actors are not yet target of such specific regulation but might be in the future. Overall the industry & energy sector is a great place to start with decarbonization efforts due to the highly centralized emission of CO_2. There are however limited options available for the decarbonization of activities in the industry & energy sector due to high temperature requirements. One of the options that is being seriously considered is the use of hydrogen as an energy carrier.

1.1.2 Vision of a Dutch hydrogen economy

One of the possible avenues for a decarbonized and sustainable energy system is referred to as the 'hydrogen economy'. The hydrogen economy is the concept of an energy system in which hydrogen is used as one of the main energy carriers. The products of hydrogen reacting with oxygen are energy and pure water. Which is in contrast with fossil fuels that produce energy and greenhouse gasses when combusted. However, elimination of greenhouse gasses from the value chain still depends on the method of hydrogen production. The bulk of hydrogen is currently produced out of natural gas through a process called Steam Methane Reforming (SMR). In this process hydrogen, carbon monoxide (CO) and carbon dioxide (CO_2) are produced. The carbon monoxide can be used in various industrial processes, but the CO_2 is emitted into the air. The hydrogen produced in this manner is generally referred to as 'grey hydrogen', due to the fact that there is no actual reduction in CO_2 emissions. An option to reduce the CO_2 emissions within this process is by capturing the CO_2 and store it under the ground in for instance empty natural gas fields, referred to as carbon capture & storage (CCS). With modern CCS technologies roughly 85% or more of the CO_2 emissions can be captured for the production of hydrogen (Simbolotti, 2010). Hydrogen produced in this manner is referred to as 'blue hydrogen'. Another method of producing hydrogen is by electrolysis of water, in which electricity is used to split water in hydrogen and oxygen. If this electricity is generated by renewable energy sources, the hydrogen is referred to as 'green hydrogen' since there are no CO_2 emissions during the production of hydrogen. Green hydrogen is the core argument for the development of the hydrogen economy, since it presents a clear recourse for decarbonizing the current energy system and increasing flexibility of the energy system through hydrogen storage.

Additional benefits of hydrogen as an energy carrier are that hydrogen can be used as a fuel in almost any application where contemporary combustion of fossil fuels is used to generate heat. Additionally, energy transport over long distances by using hydrogen as an energy carrier is cheaper and more efficient than using electricity (Wijk & Hellinga, 2018). And finally, hydrogen shows great potential for long term energy storage. In politics the hydrogen economy is seen as very attractive due to the fact that the combination of hydrogen as an energy carrier combined with renewable energy sources presents an opportunity for many countries to become less dependent on other countries for their energy supply (Marbán & Valdés-Solís, 2007; McDowall & Eames, 2007; Moreno-Benito, Agnolucci, & Papageorgiou, 2017; Nastasi & Lo Basso, 2016). The assumption is that in a sustainable energy system most of the energy production will need to flow from RES, but it is difficult to deliver high temperature with electricity alone. Hydrogen as an energy carrier can be the physical solution to the problem of linking heat and electricity in the transition towards a future sustainable Dutch energy system (Nastasi & Lo Basso, 2016).

The reason why hydrogen as an energy carrier is especially being researched in the Netherlands is due to the presence of a mature gas distribution infrastructure. In the year 1959 the gas reservoir of Slochteren (2700 billion m^3) was discovered and large-scale exploration of natural gas started in the Netherlands. The Netherlands instantly became energy independent, and shortly after the Netherlands heavily invested in the development of the natural gas infrastructure. Within a decade virtually all households were connected to the natural gas network and utilizing natural gas to satisfy their energy needs. The estimated value of this infrastructure is estimated to be €15 billion. In order to adjust this infrastructure in order for it to partially accommodate hydrogen and create a 'hydrogen backbone' is estimated to be €1.5 billion, figure 1 (De Waterstof Coalitie, 2018).

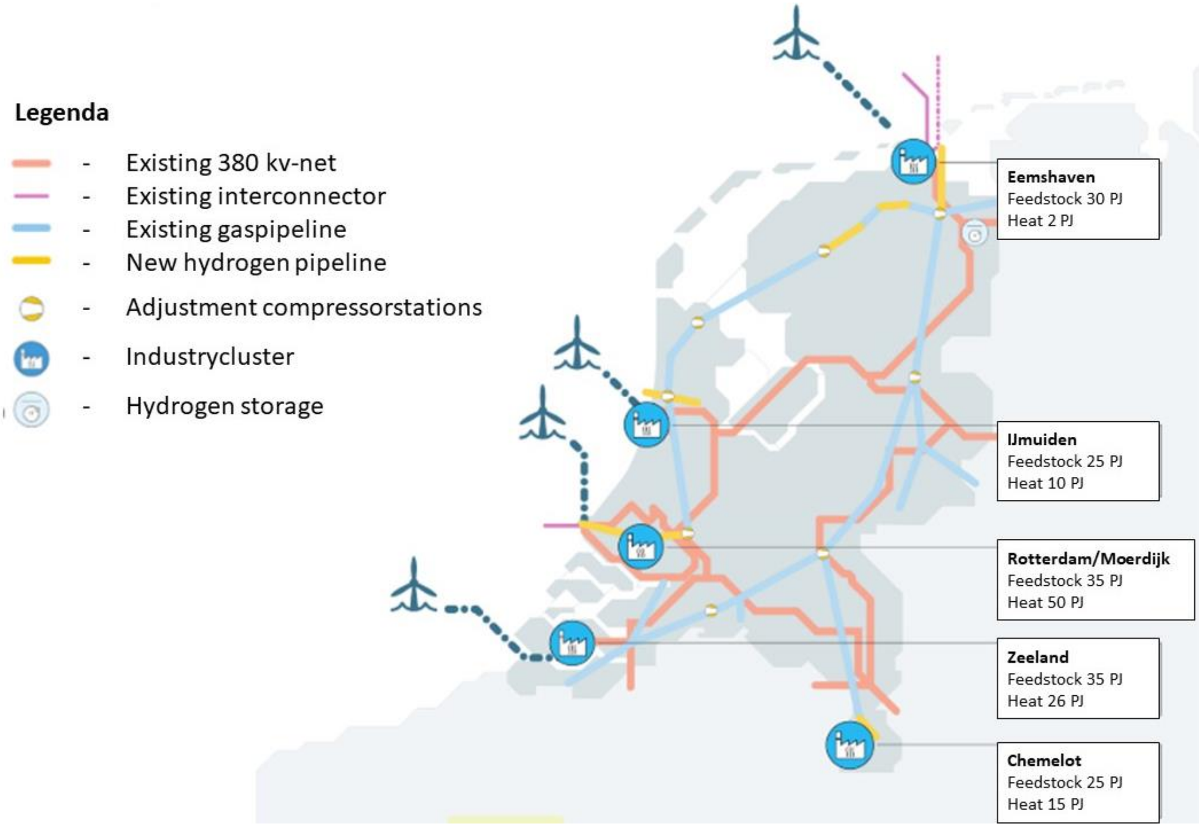

Figure 1. Main gas and electricity infrastructure in the Netherlands; with current hydrogen consumption in industry hubs (adapted from: Waterstof Coalitie, 2018).

Currently, the size of the Dutch hydrogen market is estimated to be in the order of 9 to 10 billion m^3, which translates to 0.8 to 0.9 Mton and a yearly production of 113.6 to 127.8 PJ[1] of hydrogen (Hers, Scholten, van der Veen, van de Water, & Leguijt, 2018). Around 80% of this hydrogen is produced by using natural gas in either the processes SMR or auto thermal reforming (ATR) without CCS, and 20% is a byproduct of chemical processes. About 60% of this hydrogen is used to produce ammonia, and the rest is used as feedstock in the (petrol)chemical industry. Blue hydrogen has recently been established as an economical and feasible method to implement hydrogen in the Dutch industry, for

[1] Based on a Higher Heating Value of hydrogen: 142 MJ/kg

which it is one of the few CO_2 reduction strategies. Until the year 2030, the CO_2 footprint of blue hydrogen[2] is calculated to be similar to that of hydrogen produced by electrolysis[3] (CE Delft, 2018). It was concluded that with the current Dutch energy mix the CO_2 footprint is the smallest for production of hydrogen by ATR, followed by electrolysis and SMR. Until the energy mix virtually consists of renewable energy the production and combustion of blue hydrogen for high temperature industry is seen as the most optimal decarbonization option. There are various organizations in the Netherlands that are working towards the further development of forms of hydrogen production and industrial applications. These organizations attempt to further development of the hydrogen economy and are now in a critical phase, the adaptation phase. Bridging the gap between isolated demonstration projects and a pre-commercial phase, i.e. bridging the valley of death. One of these projects is the H-vision project, an attempt by a consortium of industry actors to decarbonize their activities in the Port of Rotterdam by producing and using blue hydrogen.

1.2 CASE: H-VISION

In 2018 TNO executed a desk study called 'the H-vision Project' reviewing various options for the Port of Rotterdam to adhere to the short-term 2030 emission reduction requirements. The H-vision Project became a proposal for a dedicated Port of Rotterdam energy transition project with the fundamental principles that:

- existing assets, to the extent they can be converted to climate neutral operations, ought to be used at least for the period until they are fully written off;
- investments in H-vision should already prepare infrastructure which can be used in due time by sustainable utilities and plant operations;
- H-vision facilities, as the source for climate neutral hydrogen and power, are to be replaced at the end of the transition period by fully sustainable solutions.

In essence the H-vision project desk study examined the possibilities of replacing natural gas, refinery gas and fuel oil by blue hydrogen as an energy carrier, in the existing Rotterdam chemical, refining and power operations. Currently, hydrogen is already used as feedstock for chemical processes and oil refining processes. Within H-vision hydrogen would not only be used as feedstock but also as energy carrier to generate the necessary heat for these processes. The H-vision project is thus an attempt to integrate hydrogen as an energy carrier in the current energy system, and to kick start the Dutch hydrogen economy. Within H-vision, blue hydrogen will be produced through natural gas reforming/gasification, either by steam methane reforming (SMR) or autothermal reforming (ATR). This process will be implemented in one or more newly-built, central facilities using natural gas, refinery gas and steam as feedstock. All CO_2 generated in this process will be captured and permanently stored in depleted offshore gas fields. A basic representation of this project is presented in figure 2. These activities could possibly ensure the continuation of the industry sector in the Port of Rotterdam while adhering to the decarbonisation mandates set by the Dutch government.

[2] Blue hydrogen CO_2 footprint: 0.82-1.12 kg CO2-eq./kg H2
[3] Green hydrogen CO_2 footprint: 0.92-1.13 kg CO2 eq./kg H2

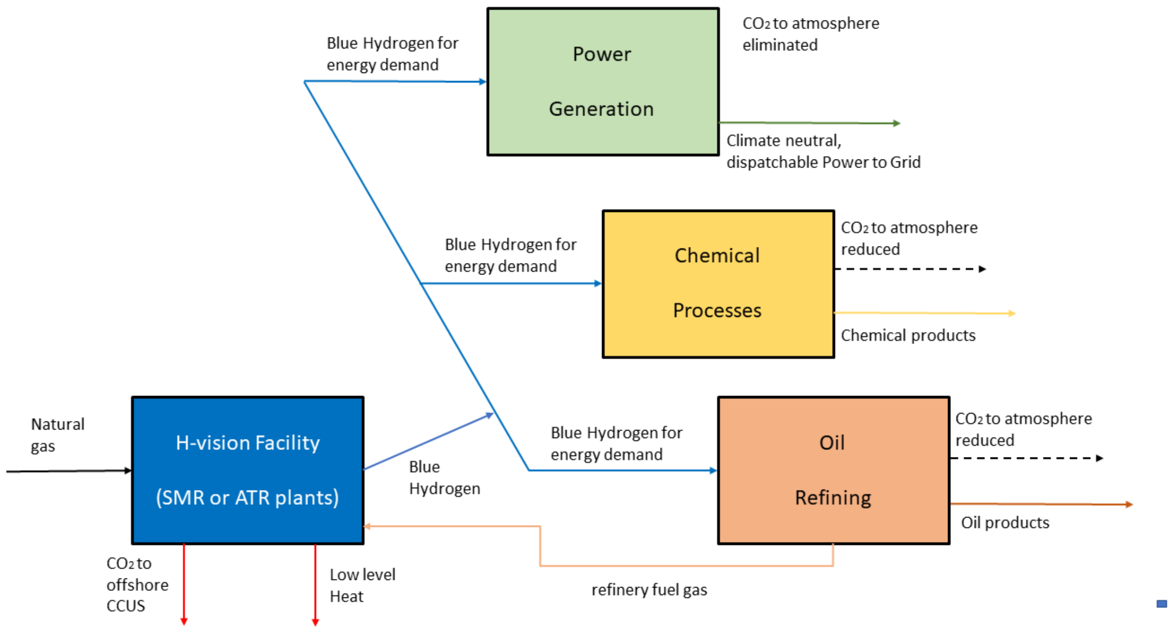

Figure 2. H-vision Project facilities integrated in Port of Rotterdam Industry.

The desk study concluded that it was possible to decarbonize the Industry in the Port of Rotterdam through use of blue hydrogen, and thus the H-vision project was upgraded to a feasibility study. A Joint Industry Project (JIP) cooperation was established with the founding partners: N.V. Gasunie; Shell Nederland B.V.; Statoil Holding Netherlands B.V.; Uniper Benelux N.V.; Engie Nederland B.V.; Enecogen V.O.F.; Air Liquide Industrie B.V.; Linde Gas Benelux B.V.; Taqa International B.V.; OCI Nitrogen; Havenbedrijf Rotterdam N.V.; Deltalings; GasTerra B.V.; Equinor; VOPAK Management B.V.; BP Raffinaderij Rotterdam B.V.; and TNO. Some of which would act on the supply side and some would act on the consumer side of the new hydrogen market. This JIP cooperation would together execute a feasibility study for H-vision. Within this feasibility study the following topics were to be covered: [1] business models with underlying economics for investors; [2] an appropriate project risk and risk mitigation register; [3] a first round of negotiations with Dutch and European Authorities to understand their willingness and capabilities to support the Project where needed; and finally [4] what service agreements are needed to govern the relations between supply and demand.

The results of the H-vision feasibility study provided several interesting and viable business models available for decarbonisation of industry in the Port of Rotterdam. However, it has already become clear that in order for any of the business model options to be developed, government support is needed. The first financial calculations within the feasibility study indicate that there will be a financial gap present in every business model option. Thus, in the next phase the government has a crucial role and can ‘crush’ or ‘make’ the H-vision project. If the government is to fill this financial gap, it will need a comprehensive understanding of how this project will affect the Dutch energy system. Specifically, what the ramifications are of each business model option. Which business model should be supported for development and integration, and how should the support be given form?

Key periods of innovation that led to growth, have witnessed the state as market 'creator' and 'shaper' not simply as market 'fixer' (Mazzucato, 2011). This study will thus attempt to provide an answer to how a partnership between public actors and the private partners can stimulate innovation in the Dutch energy system by jointly adjusting the design of the business model, energy system, and energy market, to accommodate H-vision. If H-vision is developed it would mean the realization of the world's largest blue hydrogen production unit. And simultaneously creating a substantial niche in the energy system in which hydrogen is used as an energy carrier. Decisions within the development of H-vision will create a path dependent process for the hydrogen economy and the Dutch energy system. If the right decisions are made the project becomes a success. It could then be used as an excellent reference case and foundation for future hydrogen economy developments in the Netherlands or abroad. The flipside is that if flawed decisions are made, a disadvantageous lock-in effect might cause negative and unwanted externalities in the future. Which must obviously be avoided at all costs.

1.3 PROBLEM STATEMENT

The issue with most energy transition projects is that the basic problem is not owned by one specific party. This makes that the business model is validated according to different standards by both companies and the government. The business model for H-vision will be assessed according to its profitability by the collaborating companies, if the profitability is not satisfactory it will not be developed. The government however is interested in the effects of H-vision on the Dutch energy system. It creates regulation in order to maintain the stability and reliability of the energy system. Due to the unbundled nature of the Dutch energy system a public private partnership (PPP) is necessary to integrate sustainable energy technologies such as H-vision into the Dutch energy system. A PPP is a durable collaboration between private and public actors in which both sides share risk, costs and benefits when developing beneficial products and/or services (Klijn & Teisman, 2002). In order to properly analyze such an endeavor, in this case H-vision, a more comprehensive manner of business modelling is necessary. There are many frameworks available that can help guide the process of finding these effects. However, it is my opinion that there are none that specifically cover the combination of business models with system effects to properly reflect the interests of all stakeholders. I will substantiate this opinion in the following paragraphs.

Technological innovation and its integration into the system presents new opportunities to create and capture value. Each innovation, system integration and product development effort should be combined with a business model that defines the strategies for market penetration and capturing value. A business model represents the basic logic of the firm and its architecture to remain relevant in its environment. As Shafer, Smith & Linder (2005) state: "*a business model is a representation of a firm's underlying core logic and strategic choices for creating and capturing value within a value network*". The necessity for a business model is especially high when technological innovation occurs and needs to be integrated within these market economies (Chesbrough & Rosenbloom, 2002). Currently the process of introducing and integrating new technological innovations in the energy system is accompanied with major investments. These investments are made to ensure profitability and the payback period, in most cases, extends over more than a decade. The investments need to be well-justified towards stakeholders. The result is that business models are often purely designed around these new technological innovations with a strong focus on financial aspects. This chain of reasoning is not entirely acceptable, especially in energy systems which are connected to broad social interests.

Business models are a management tool to assess costs, deal with the business environment and acquire competitive advantage. The importance of the environment cannot be understated when developing business models, as argued by Teece (2010): "*Neither business strategies, business structures nor business models can be properly calibrated absent assessment of the business environment; and of course the business environment itself is, in part, a choice variable; i.e. firms can both select a business environment, and be selected by it: and they can also shape their environment"*. Implying that both the business model and the system should be designed together. Currently, there are several business model ontologies and other business model studies. Nevertheless, they fail to properly address the broader environment, which has also been acknowledged by Foss & Saebi (2016). The broader environment must be addressed to understand the social value and externalities of a business model to be integrated in the Dutch energy system. Within this study the concept of a business model is: "the manner in which an organization or a network of organizations within a broader system intends to create and capture value from the integration of a technological innovation". If firms fail to properly address costs in a system related manner, they will risk failing in capturing value. Most likely resulting in them losing their competitiveness and their ability to succeed commercially.

Literature that is useful to analyze this broader environment is that of socio-technical systems and their design. Contemporary work on socio-technical systems has increasingly shown a tendency to favor the social and dynamic aspects of socio-technical systems, such as: innovation, adoption, diffusion and policy (Carlsson, Jacobsson, Holmén, & Rickne, 2002; Geels, 2004; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007a; Markard & Truffer, 2008; Ortt & Duin, 2008; Ortt, Langley, & Pals, 2013; Schot & Geels, 2008). Slowly the interdisciplinary knowledge and the coupling of both social and technical design, once thought to be critical, has slowly been phased out of literature concerning socio-technical systems. This was recognized by Scholten & Künneke (2016), when looking at the socio-technical aspects of energy infrastructures. They observed the growing chasm between on one side economists that focus on market design and on the other side engineers that focus on infrastructure design.

Summarizing, there is a need for scientific literature to holistically combine the process of making business models in complex socio-technical systems with perspectives that address the design of the systems infrastructure and market. Fusing these streams can be very helpful for making projects developed by PPPs a success. If they did, the amount of attention given to technological change was minimal. Vice versa, effects of the business modelling and indirectly the role that the decisions of actor's play are important to incorporate in the design of complex socio-technical systems such as the energy system. Giving clarity on the influence that system integration of specific technological innovations can have on the system. Additionally, and perhaps most crucial, there is a practical knowledge gap on how the government can or should accommodate the H-vision project. The underlying cause are the uncertain effects of integrating hydrogen as an energy carrier on the Dutch energy system. This is endorsed by the fact that very few studies make any reference to theoretical literature concerning technological change when addressing potential hydrogen futures (McDowall & Eames, 2006). Especially, concerning matters regarding transport, import, export and storage of hydrogen (Amirante, Cassone, Distaso, & Tamburrano, 2017; Barreto, Makihira, & Riahi, 2003; Dunn, 2002; Elam et al., 2003; Hanley, Deane, & Gallachóir, 2018; Kurtz, Peters, Muratori, & Gearhart, 2018; Marbán & Valdés-Solís, 2007; Preuster, Alekseev, & Wasserscheid, 2017; Sharma & Ghoshal, 2015).

1.3.1 Knowledge Gaps

Business models with attention to the system and market design need to be conceptualized in order to assess the integration of hydrogen as an energy carrier and the effect it has on the Dutch energy system. This will stimulate and help actors with further development. Knowledge gaps are therefore identified as follows:

- It is unknown how to judge and improve the outcomes of public-private partnerships for energy infrastructure projects
- It is uncertain how literature on socio-technical systems are to be combined with literature on business models;
- It is uncertain what the dynamics are between the business model options for blue hydrogen and the specific system and market designs;
- It is unclear how the Dutch government can facilitate the H-vision project;
- It is unclear what kind of effect the integration of the H-vision project can have on the Dutch energy system.

Generating an answer for the above-mentioned knowledge gaps can lead to valuable insights for catalyzation of a sustainable Dutch energy system and the Hydrogen economy in general. The focus will not be aimed at a designing and modelling extensively detailed energy systems due to the time constraint of this research. It will thus rather be to provide an educated exploration on the combinations of system design and business modelling for H-vision to distill the implications of these combinations. A framework that addresses the business model and system design in a holistic manner will be of value to improve the broader system performance and help the further diffusion of a specific innovation or system integration. This also applies to the H-vision project, since this can be seen as a pilot project that might strongly influence the integration and further diffusion of hydrogen as an energy carrier. Consequently, advice can be given for the sequence of measures that can be designed to bring about a desirable future, avoid market failure and technological lock-in.

1.4 Research objective

It is still uncertain how the hydrogen as an energy carrier can be successfully integrated into the Dutch energy system. As stated, the difficulty lies in the absence of a comprehensive business model framework with which the actors in the PPP can operate and, synchronize their activities in order for them to become complementary. Therefore, the objective will be to create and appraise a new conceptual framework which combines classic business model literature with literature on complex socio-technical systems.

Research Objective

To assess the performance of the H-vision business models when system design effects are also included.

1.4.1 Research Question

When considering the knowledge gaps and research objective of this project as presented in 1.5 and 1.6 respectively the main research question is defined as:

> ***Main research question***
>
> *How does the performance of the H-vision business models change when system effects are incorporated in the design?*

To properly answer the main research question, additional sub research questions need to be identified and formulated. These sub-research questions are formulated in such a way to cover the four knowledge gaps presented in section 1.5. The sub-research questions are defined as follows:

1) How to combine business model theory with socio-technical system literature?
2) What are the business models for the H-vision options, and what are logical/realistic system designs for the integration of blue hydrogen?
3) Does comprehensive business modelling lead to an improved business model for H-vision and its successful integration in the energy system?
4) How does the new framework rival current business model and system integration ontologies; and does it create a better understanding of complex technical integrations in the energy system?

1.4.2 Research relevance

The direct practical relevance resides within the request for this research that originates from the private sector. Berenschot, a consultancy firm has partnered with 15 other organizations and corporations in the H-Vision project to assess the possibilities for decarbonizing the Port of Rotterdam. Berenschot and their partners are the main party interested developing this project to produce and consume blue hydrogen as an energy carrier in the Port of Rotterdam. Berenschot is interested in this thesis project due to the fact that in the next phase the government has a crucial role in the further development of the H-vision project. Especially since it can help them convince the Dutch government to fill the financial gap. This thesis project is executed in collaboration with Berenschot and to lesser extent the other H-vision partners.

The academic relevance of this research resides in the contribution to the body of literature concerning business models and complex socio-technical systems, by addressing the previous presented knowledge gaps in the scientific literature. A well performing business model for a PPP will lead to an improved performance of the socio-technical system. Additionally, this research will be a suitable addition to the growing and societal relevant body of literature concerning energy transition projects. The energy transition is a multi-facetted problem, a large number of scientists are proposing varying solutions either from an engineering or economic perspective. It is my hope to bridge these two perspectives and explore the possibility of hydrogen as an energy carrier in the Netherlands. This might invigorate the open and imaginative discussion concerning how we can achieve a sustainable future.

The societal relevance is situated in the value of a sustainable energy system, which is beneficial for the Dutch society as a whole. Climate change and global warming can have significant effects on the continuity of the Netherlands. Especially since such a large part of this country is below sea level and situated in a delta. Aside from natural disasters a more sustainable energy system will benefit the health of the Dutch population and reduce pollution.

1.5 RESEARCH DESIGN

The scope of this research is to identify and address the aspects of the business models' options and their system integration. Consequently, the effects of these aspects on the further development of the hydrogen economy in the Netherlands. The three business model options currently proposed are presented in table 2. The most defining characteristics for these business models are: H_2 Demand, CO_2 storage, and infrastructure development needed.

	Minimal option	Medium Option	Maximum Option
H_2 Demand	1139 MW	3207 MW	5202 MW
CO_2 Storage	2.2 Mton/year	5.5 Mton/year	9.4 Mton/year
Infrastructure development needed	New local pipeline; no storage needed	New dedicated pipeline network; no storage needed	New dedicated pipeline network; storage needed

Table 2. Business model options H-vision.

The research design for this thesis project is an applied and embedded single case analysis. Applied in the sense that existing theories will be applied to solve a specific business problem, in this case the development of the H-vision project. The single case of H-vision is used mainly due to the practical availability, but also as a means to question old theoretical relationships and explore new ones (Gustafsson, 2017). The embedded part stems from the analysis of more than one sub-unit within the H-vision project. It is my ambition to create and use a comprehensive framework consisting of three analytical constructs. The streams of literature that lie at the basis of this framework are that of: 'socio-technical systems' and 'business models'. These constructs are in turn made of specific criteria that according to literature serve as denotations of the construct. Two of the constructs will have a direct effect on the last construct which is the performance of the project and socio-technical system combined. The project in this case is the H-vision project, and the socio-technical system is the energy system.

1.5.1 Analytical Framework

The integration and further development of hydrogen as an energy carrier and a hydrogen infrastructure is negatively affected due to the absence of a system integration approach when creating business models. This chapter will provide the basic foundation upon which the thesis project can be built.

The first stream of literature is that of the development of business models. Business models were first used to build the architecture for building information technology systems (Bouwman, De Vos, & Haaker, 2008). However, slowly business modelling has evolved into the study of the correlation between certain data and organization decision making. Business models have become increasingly related to the strategic choices firms are making and consequently the formation of markets (Hedman & Kalling, 2003). The main dimensions of business models are: the partners, activities, resources, value proposition, customers, communication channels, costs and revenues (Osterwalder & Pigneur, 2005). Business model ontologies generally deal with the assessment of these dimensions. When this has been done in clear manner the manager(s) can make decisions that benefit the organization. Put differently a business model reflects management's hypothesis of how the organization or a network of organizations can best create and capture value by producing a new technological innovation or integrating it into one of their systems. The manner in which they can create, and capture value largely depends on the market. One of the most used ontologies to understand the market and the value potential of a business model is the CANVAS model, which focuses on linking strategy into business processes. The CANVAS model has nine building blocks which are: customer segments, value proposition, channels, customer relationships, revenue stream, key resources, key partner ships and cost structure (Osterwalder & Pigneur, 2010). As can be seen not much attention is given to the technology or product itself and the place it has in the system. Addressing these aspects can be done by the second stream of literature used in this thesis project.

Socio-technical systems literature is the second stream of literature. It attempts to combine the differentiated production and consumption perspectives of technology. Evolutionary economics, business studies and innovation studies have a strong tendency to focus on the production side of technology. Assuming that the consumer of technology is just 'out there'. While cultural and domestication studies focus to much on the consumption side, arguing that consumption is more than only buying and adoption. However, these consumer-focused perspectives fail to address the development of technology. The advantage of looking explicitly at socio-technical systems as Geels (2004) argues: "*is that the co-evolution of technology and society, form and function becomes the focus of attention"*. The main analytical dimensions within this stream of literature are: the technical systems; rules and institutions; human actors, organizations and social groups. Dynamics of these dimensions are categorized as certain exogenous factors, rule systems, decision making, and learning mechanisms. Misalignment in the dynamics of these dimensions are at the core of many structural problems modern societies face today. Socio-technical ontologies are based upon the premise that these problems can be solved by aligning these dynamics. Combining these two streams of literature might provide useful insight in finding the effects of integrating technologies into complex socio-technical systems. The combination will provide a new theoretical framework.

This framework will have three main constructs, an outcome construct representing the system after integration and two preceding constructs that provide the narrative of how this outcome is or has become to be. The first construct contains the factors that make up the "*Business model"*, aspects of theory concerning 'business models' and 'strategic niche management' will be used to select the most important criteria (Heikkilä, Bouwman, Heikkilä, Solaimani, & Janssen, 2016; Ortt et al., 2013; Schot & Geels, 2008). The second construct contains the factors that define the '*System blueprint'*. The factors used in this construct originate in theory on the 'comprehensive design framework of energy infrastructure' (Scholten & Künneke, 2016). For the "*Outcomes"* construct, theory on 'competitive advantage of nations', theory on diffusion of innovations, and theory on the geo-politics of renewable energy will be used in addition to the previous mentioned theories to establish the performance of the comprehensive business model (Porter, 1990; Scholten, 2019; Utterback, 1994). In short, the literature study method will thus be used to provide this thesis project with a sound theoretical basis in order to establish enough rigor. Combining these streams of literature into one conceptual framework will help in answering the second sub-research question. A preliminary sketch of this framework is presented in figure 3. Summarizing, I propose the following relation between the main theoretical constructs. There are two independent constructs that have an influence on the dependent construct which is the proper functioning of the socio-technical system. The constructs, '*Business Model*' and '*System blueprint*' and their inner workings are very well presented within current scientific literature. Their interrelation and their combined effect on a socio-technical system however are not. The main knowledge gap and uncertainty if their combined effect is indeed significant and therefor relevant to analyze and/or design in a unified way. This paper will aim to test this framework according to the H-vision project.

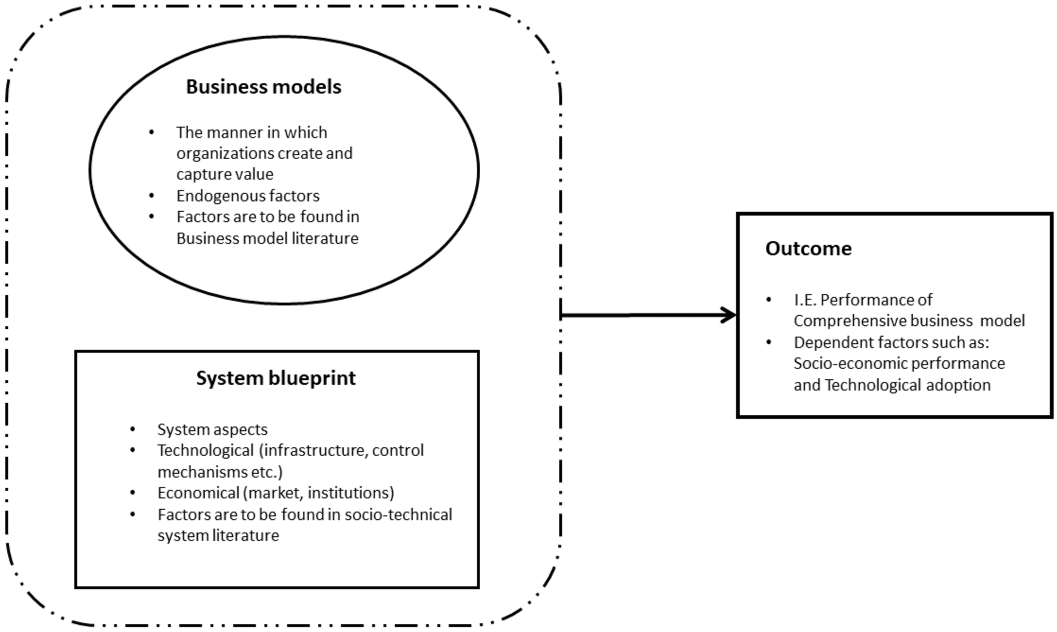

Figure 3. Preliminary sketch analytical framework.

The usefulness of this framework will be assessed through its application and it can provide answers for the remaining sub-research questions. Hopefully the framework provides useful insights towards further development of a sustainable Dutch energy system and hydrogen economy. Possibly other countries, most likely countries in the EU, can use the framework within their energy system transformation activities as well. Emphasis on focus areas within the hydrogen research agenda varies with countries; communication and cooperation to share research plans and results are essential (Preuster et al., 2017).

In order to execute this case study analysis, the following protocol will be used. At first, the theoretical framework will be established. Then, the three business options and system designs used for the application of this framework will be explained. Accordingly, the framework will be applied. Data on H-vision and the broader environment will be analyzed for the presence of any criteria given in the framework as discussed in the previous sections. This data can then be used to assess the presence and level of the criteria that make up each block. By analyzing these criteria, we can discern the most important aspects of the business model and choices made by actors in the consortium; influences of specific system and market design; and the outcome of the integration of blue hydrogen into the energy system. As such possible combinations can be made with an emphasis on the technical feasibility, pros/cons and implications of the different options. Upon this basis we can discuss what might be a desirable end state for the Dutch energy system resulting from integration and adoption of hydrogen as an energy carrier.

1.5.2 Research Methods

1.5.2.1 Literature study

A literature study is a qualitative secondary analysis (desk research). This literature study will be performed by collecting qualitative data and/or synthesis of existing data, which has already been collected for other purposes than this research (Bryman, 2012). This method is found to be best suitable for this thesis project because: it saves costs and time in collecting data, existing data is high-quality and collected over a longer period of time (Bryman, 2012).The existing data will be taken out of peer-reviewed articles, company and NGO reports and news articles. Peer-reviewed articles will be acquired through the licenses of the TU Delft. In order to satisfy the first three sub-research questions a literature study will be performed in order to gain data and synthesize a new conceptual framework. Additionally, a literature study will be performed for the last question to determine the usefulness of the new framework.

1.5.2.2 Expert identification

The relevant experts are identified through their participation in the H-Vision project or similar projects. Additionally, a 'snow-balling' technique will be utilized in which (potential) candidates for interviews are asked to identify further relevant stakeholders to guarantee that no vital interests and perspectives are missed.

1.5.2.3 Expert Interviewing

Expert interviewing is done in order to obtain information from experts and is regarded as a qualitative empirical research method (Bryman, 2012). The basic technological and economical quantitative data will be validated. Then, the experts will confirm the factors that they utilize in either business modelling and design for the system in which the project will be integrated. Next, the factors found in literature are discussed to see if the expert has conveyed identical factors. If a difference exists between the factors mentioned by the expert and the factors found in the literature. The ensuing question will attempt to find the reason for this variance.

Sub-research questions	Research Method	Research goal
How to combine business model theory with socio-technical system theory?	Literature study and expert interviewing	Elaborating on theories that help define the constructs of analysis. Developing the framework and identifying metrics needed for operationalization.
What are the business models for the H-vision options, and what are logical/realistic system designs for the integration of blue hydrogen?	Case study, Literature study, and Expert interviewing	Exploring and providing information on the business models Establishing the technical design and market design for integrating blue hydrogen with experts within the Dutch energy system.
Does comprehensive business modelling lead to an improved business model for H-vision and its successful integration in the energy system?	Framework application, Expert Interviewing, and Discussion	Assess the performance of the comprehensive business model of H-vision by using the new framework.
How does the new framework rival current business model and system integration ontologies; and does it create a better understanding of complex technical integrations in the energy system?	Literature study, and Discussion	Research comparable methods and analyze performance of conceptual model in relation to these methods in a critical manner.

Table 3. Overview sub-research questions in relation to research methods.

2 THEORETICAL FRAMEWORK

In this framework the theoretical framework is explained. At first the energy infrastructure is coupled to the definition of a socio-technical system. Then, the constructs i.e. the Business Model, System Blueprint, and System performance are described. With emphasis on their denotation and the important factors that can be used to assess these constructs. Consequently, these constructs are combined into an analytical framework, which defines the interrelation between the constructs. Finally, the operationalization and application of the framework are addressed.

2.1 ENERGY SYSTEM AS A SOCIO-TECHNICAL SYSTEM

The concept of socio-technical systems was conceptualized in the 1950s in relation with postwar reconstruction of industry and the diffusion of innovative work practices (Trist, 1981). One of the first to address the need for an interdisciplinary approach to complex system building was Boulding (1956). Boulding however gave warning that the interdisciplinary research approach must not degenerate into the undisciplined. Soon afterwards Emery (1959) proposed an general model that included the social and technical dimensions of system design. Arguing that although the technical and social systems are independent of each other, one adhering to the laws of nature and the other to the laws of humans. They are still correlative in the sense that one requires the other for the transformation of an input into an output, which in effect constitutes the functionality of a system. Emery (1959) argued therefore that: "*Their relationship represents a coupling of dissimilars which can only be jointly optimized. Attempts to optimize for either the technical or social system alone will result in the sub optimization of the socio-technical whole.*" In short, the social and technical aspects of such complex socio-technical systems need to be aligned. If alignment is successful, they can complement each other and become drivers for future output and development, if this alignment fails their contradictions can form barriers to future output and development.

There are five key characteristics according to which a socio-technical system can be recognized (Baxter & Sommerville, 2011; Righi & Saurin, 2015). [1] The system has interdependent parts, i.e. diversity of the system; [2] the system can adapt to and pursue goals in the external environment, i.e. variability of the system; [3] the system is made up of separate but interdependent technical and social subsystems; [4] system is resilient and goals can be achieved in multiple ways, implying that design choices are necessary during system development; [5] system performance relies on the joint optimization of the technical and social subsystems.

When taking into account these characteristics the Dutch energy system can be seen as a socio-technical system. [1] The system has a vast amount of interdependent parts. The infrastructure, the production of energy, the consumption of energy and everything in between is linked. [2] Currently, the Dutch energy system needs to adapt to goals in the external environment, i.e. the climate goals set by the United Nations. [3] The Dutch energy system is constructed around a technical core of physical artifacts, i.e. electricity & gas grid, and embedded, controlled and sustained by an intricate composition of social institutions. [4] In order to adhere to the climate goals, set by the Dutch government, the current transition of the energy system can be achieved in various ways. This is due to the many methods in which energy can be generated. [5] The physical and economic aspects of the Dutch energy infrastructure enable natural monopolies to occur which constitutes a market failure. If this is not addressed by regulation a market failure is very likely to ensue. The joint optimization of both the technical and social subsystems in the Dutch energy infrastructure is a continuous process of interaction between the public and private sector.

2.2 Constructs

2.2.1 Design Construct #1: Business Model

Business models have become increasingly related to the strategic choices firms are making and consequently related to the formation of markets and systems (Hedman & Kalling, 2003). A business model is simply put an aggregation of choices made by a firm in order to create and capture value. In the past decade, interest in the concept of business models has grown virtually exponentially. Every company has a business model, whether they have come to realize it or not. The idea that managers can purposefully innovate their business model to gain competitive advantage was first explicitly discussed by Mitchell and Coles (2003). Currently it no longer purely is a tool for competitive advantage but a tool for survival as well. The increased frequency of technological disruption and system change in many industries is shortening business model lifecycles. Companies thus need to integrate its innovation process within its business model and need to see their business model as an adaptive platform (Henry Chesbrough, 2007). Business models are being used to understand and classify value drivers and are argued to be a constructive factor to company performance. Which is logical, some companies outperform others and their successful business models are seen as examples to be imitated. A business model covers the company’s value proposition, market segments, the structure of the value chain required for realizing the value proposition, the mechanisms of value capture that the company deploys, and how these elements are linked together in an architecture (Foss & Saebi, 2016). Business models do not necessarily constitute a construct solely for a single firm but can also be applied on a system level. Which, for this study is especially useful. Business model literature is categorized in three broad interest areas (Zott, Amit, & Massa, 2011): [1] as a basis for enterprise classification and use of information technology, especially in e-business; [2] strategic issues, such as value creation, competitive advantage and company performance; [3] as a potential unit of innovation and technology management. Since the scope of this project is the integration of blue hydrogen, which is both a strategic issue and the management of a new technology. The focus of this paper in relation to business models will mainly concern the last two categories.

Business model ontologies generally deal with the determination of the dimensions: the partners, activities, resources, value proposition, customers, communication channels, costs and revenues (Osterwalder & Pigneur, 2005). When this has been done in clear manner the manager(s) can make decisions that benefit the firm(s). Put differently a business model reflects management’s hypothesis of how the organization or a network of organizations can best create and capture value by producing a new technological innovation or integrating it into a system. In general, the design of a business model is done in a number of steps. Usually this starts with formulation of the idea, often this is stated in a strategy and developed through SWOT or Porter’s competitive forces analysis. This is followed by a requirement elicitation, in which the business model tooling is chosen and the necessary requirements for the business model are determined. The most commonly used business modelling tool to understand the market and the value potential of a business model is the CANVAS model, which focuses on linking strategy into business processes. The CANVAS model has nine building blocks which are: customer segments, value proposition, channels, customer relationships, revenue stream, key resources, key partner ships and cost structure (Osterwalder & Pigneur, 2010). The third phase is the identification of the solution, herein the business model metrics are chosen that are deemed relevant to the development of the business model. According to the chosen metrics an assessment can be made which business model has the highest value potential. Recently, a set of metrics have been synthesized out of a large set of business model tools (Heikkilä et al., 2016), presented in Appendix 1.

These metrics can be used to design or evaluate business models. They were explicitly made for networked organizational settings or ecosystems. These metrics allow the assessment of the "value network", a dynamic network of actors that are legally independent, collaborating and sometimes competing to produce a specific service or product. Eight main factors (table 3) were found to be relevant for business model design, presented in table 4 (Heikkilä et al., 2016). The succeeding phases are Prototyping; Implementation of the business model; and Evaluation. In some cases, prototyping is not necessary for the development of the business model.

Perspectives	Description
Customer	Customers are crucial to a business model, without customers a company or consortia of companies cannot create value. This factor looks at the created customer value and the market segment.
Service/Product	Focuses more the company's or consortia of companies' perspective on value delivery. This factor looks at the service development, service quality, sustainability of the service, and complementary products and services.
Technical	Technology is the core driver and enabler for business models innovation. This factor focuses on how the technology is being utilized or integrated. This factor looks at complexity in the architecture, control mechanisms, functionality, interoperability requirements, accessibility requirements, up-time requirements, technological principles, and alternative technologies.
Organizational	Focuses on core resources and capabilities that have to be made available in order to produce or integrate the technology. Resources can either be tangible or intangible. This element looks at the heterogeneity of internal partners, access to partners, and heterogeneity of external partners.
Financial	Focuses on the manner in which companies capture value. This factor looks at value of the technology in relation to the network, profitability, costs, and risks. Metrics such as CAPEX, OPEX, IRR and payback time are used.
Value exchange	Value exchange can take place throughout ecosystems, both vertically and horizontally. This element looks at the size of the partner network, contracts, importance, and value conflicts.
Information exchange	Information, tangible and tacit, has to be strategically positioned in order for it to be relevant to the value architecture. This element looks mostly at knowledge diffusion and knowledge development within the organization.
Process alignment	Operational activities of the company are often shared within a networked ecosystem. Operational processes are necessary to implement a business model. This element looks at the number of processes, throughput, and variety of these processes.

Table 4. Eight factors that characterize business models (adapted from Heikkilä et al., 2016).

2.2.2 Design Construct #2: System Blueprint

The basis for the moderating construct is the comprehensive design framework for energy infrastructure design conceptualized by Scholten & Künneke (2016). This framework links the two design dimensions of energy infrastructures. Which are system design and market design, these dimensions have various variables along four distinctive layers for an overview see figure 4 and 5.

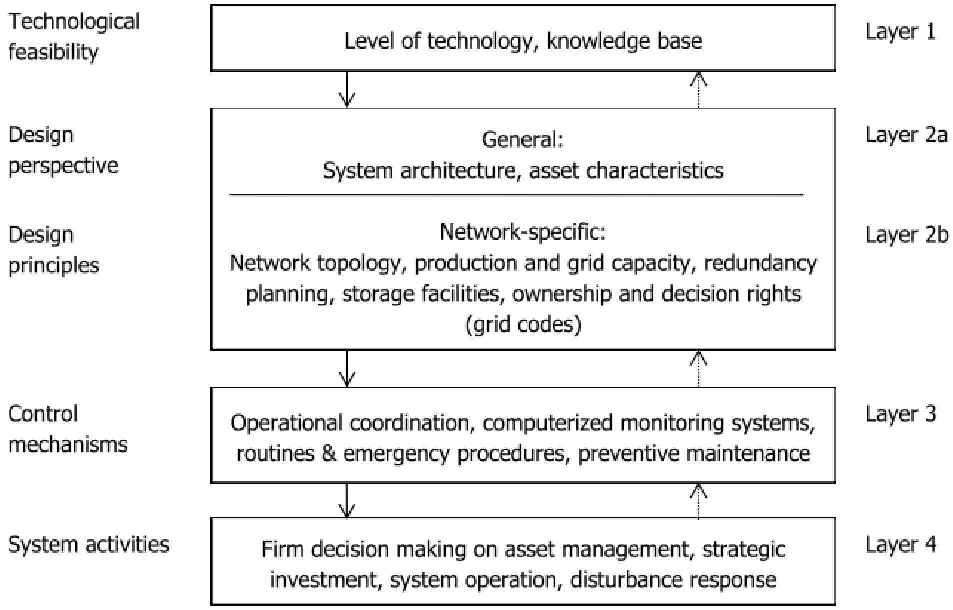

Figure 4. Four layers of system design variables in energy infrastructures (adapted from Scholten & Künneke, 2016).

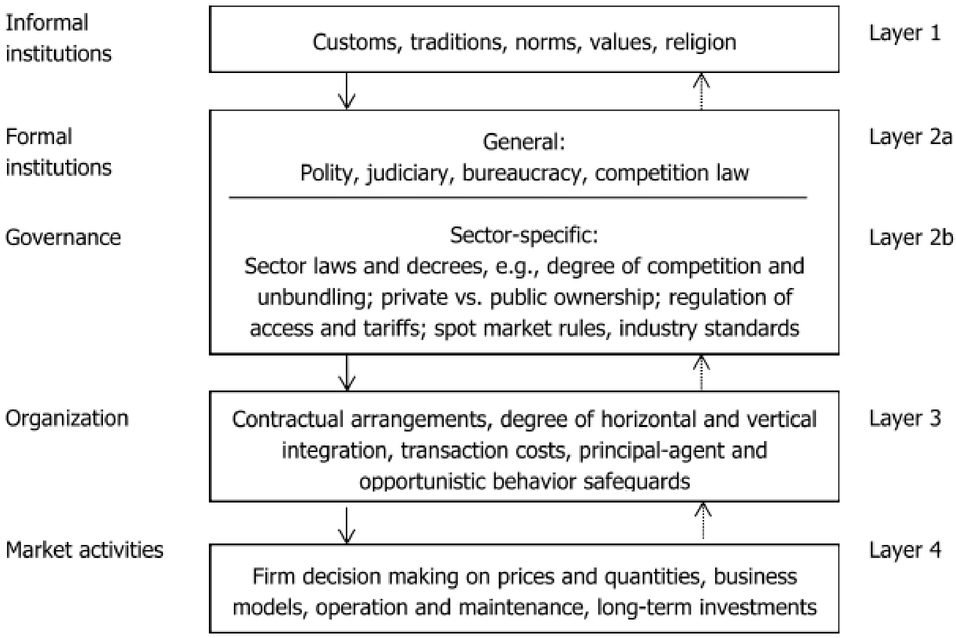

Figure 5. Four layers of market design variables in energy infrastructures (adapted from Scholten & Künneke, 2016).

The fourth layer of the market and system design factors is effectively indistinguishable with business model concepts.

The comprehensive framework builds on five premises as stated in Scholten & Künneke (2016).

- The proper alignment of both dimensions is crucial for an infrastructure to perform according to expectations.
- Whatever good or service is being provided, the techno-operational performance is expressed in the reliable and robust functioning of the energy infrastructure in question.
- The efficiency and effectiveness with which a specific good or service is provided shape the socio-economic performance of the energy infrastructure in question.
- Trade-offs exist between the performance criteria of each dimension and between the dimensions. The minimum requirements of both dimensions are not satisfied then there is either a malfunctioning (no service provision) or misfunctioning (an undesired service) of the energy infrastructure.
- The concepts applied in system and market design link to a great extent, these linkages allow aligning the systemic and market dimensions of energy infrastructures.

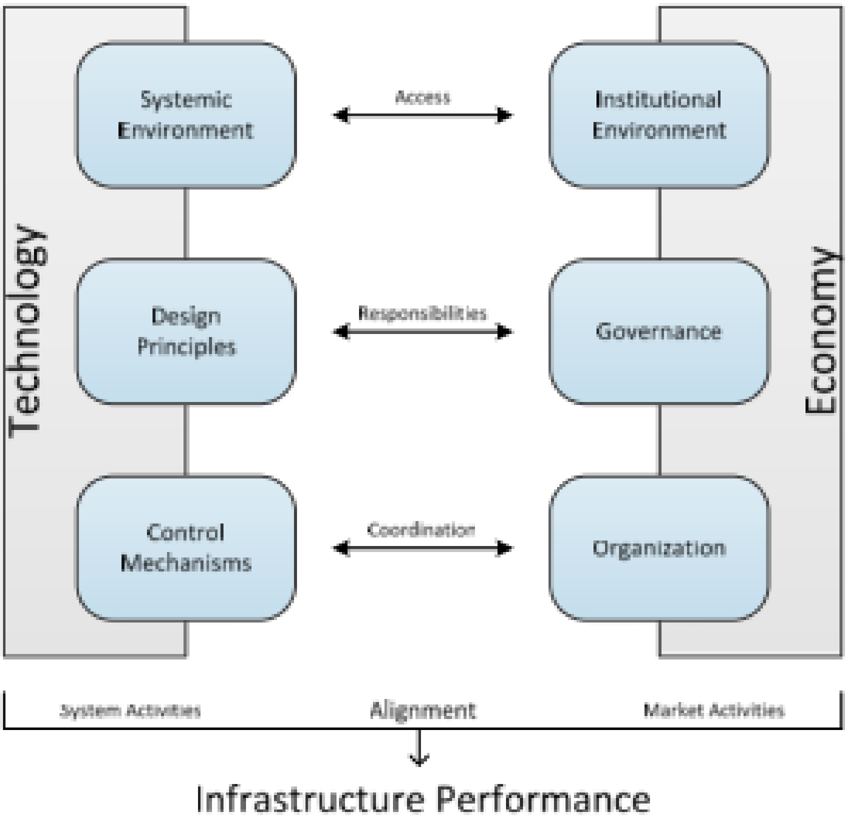

Figure 6. Comprehensive design framework. Alignment of the technical and economic design of energy infrastructures (adapted from Scholten & Künneke, 2016).

These five premises are combined in the framework presented in figure 6. The layers revolve around a set of 'design knobs': access, responsibility, and coordination. This allows the framework to link the two dimensions in a satisfactory manner. The "access" design knob refers to the relation between the systemic and institutional environment (layers 1 and 2a of Figure 4 & 5). The "responsibilities" design knob refers to the relation between the technical design principles and the market governance arrangements (layer 2b of figure 4 & 5). The "coordination" design knob refers to the relation between techno-operational coordination and market transaction among actors to produce a certain good or service (layer 3 of figure 4 & 5). It is crucial to maintain the coherence between both the design choices on the layers and across the dimensions. If this is realized the design constraints will result in actor behavior that is beneficial to the system performance, which in turn creates new economic and technological developments. This framework focusses heavily on the socio-technical design challenges that can arise in energy infrastructures. Paying rather little attention to the origins of such a design challenge, i.e. when a new value, good/service, idea, or technology emerges and is adopted by actors. Scholten & Künneke (2016) state themselves that: "*the role of actors in technical innovation and changing institutions that warrants a design effort in the first place falls outside the scope of this research".* Thus, layer four of the market and system design variables is left out of the comprehensive design of energy infrastructure framework.

2.2.3 Outcome Construct: System Performance

The final construct is System Performance, which comprises the consequences of making various combinations of technology, value creation, delivery, and appropriation mechanisms. The most favorable outcomes would be the successful integration of the blue hydrogen. Successful integration might lead to improved infrastructural, financial and innovative performance. Possibly, resulting in the large-scale diffusion of hydrogen as an energy carrier and making further steps to realizing the hydrogen economy. This construct is ideally analyzed ex post; however, this framework should be an adequate tool to express the implications of the previous mentioned constructs ex ante.

Factors	Description
1. Sustainability	Constitutes the level of acceptability of integrating the business model into the system along with the chance that the design for the business model, infrastructure and market lead to market/government failures.
2. Affordability	Constitutes the financial effects of the integrating the business model into the system. This factor will assess the degree to which the finances can be justified and are how they are allocated.
3. System robustness	Constitutes the system's ability to adapt inherent processes to optimize performance and maintained valued system outputs after the integration of the business model. Consisting out of the flexibility of the system and the provided energy security by the system.
4. Reliability of Operations	Relates mainly to the operational and technological consequences of integrating the business model into the system. What are the lifecycle characteristics of new components and to what level are these new components able to guarantee energy supply to consumers.

Table 5. Four factors that characterize system performance.

2.3 ANALYTICAL FRAMEWORK

I propose the following relation between the main theoretical constructs, presented in figure 7. The business model construct is defined by private actors according to how they want to utilize and integrate the artefact. This is where a company or collaborating companies determine if they want to develop a technology and implement it in the energy system. Often the business model is developed in a niche of the broader system, the technology is used for specific applications. To determine if companies want to continue with developing a business model, they take a number of steps and use various tools, as discussed in section 2.2.2.

The comprehensive infrastructure design construct is defined by the public actors according to what level they want the system to accommodate the artefact. In highly regulated socio-technical systems such as the energy system, the infrastructure and market must adapt to new business models. Especially in the case of the Dutch energy system in transition. New goals set by the Dutch government put pressure on current business models, but there is not enough incentive for the incumbent companies to change. An important prerequisite for the development of a business model is that the infrastructure and market allow for the venture to be profitable. In a perfect world incumbent companies within the energy sector would change their business models themselves. Even if the new business models are at first less profitable. This however is not realistic, just as we have beard witness in the past two decades. The government must design the infrastructure and market through new institutions and regulations to accommodate new business models for large incumbent energy companies.

Finally, the interplay of these two design processes are what determine the energy system performance on a macro-level. If these design processes are well aligned and coordinated, successful integration of the artefact will ensue and according to theory will result in a better performing energy system. I argue that the process of designing the business model, infrastructure, and market should not be seen as unrelated processes. Combining these processes will create a better understanding for successfully integrating novel technologies in an energy infrastructure. Especially if a swift change in the energy system is required.

This conceptual model and framework will be static in nature. The study will assess what the resulting state of the Dutch energy system will be according to the choices made in the design of the H-vision business model and the energy infrastructure & market. As such recommendations can be made as to which design creates the most overall value. I recognize that there is a dynamic facet to the integration of technologies in a system, i.e. innovation and diffusion of technologies. Which is a bi-directional process, characterized by drivers, barriers and windows of opportunity, that influence the life-cycle of new high-tech products. This aspect of technological integration will not be within the main scope of this study. However, I do find that the dynamic of aspect of technology integration can provide important context and will cover it in the discussion chapter.

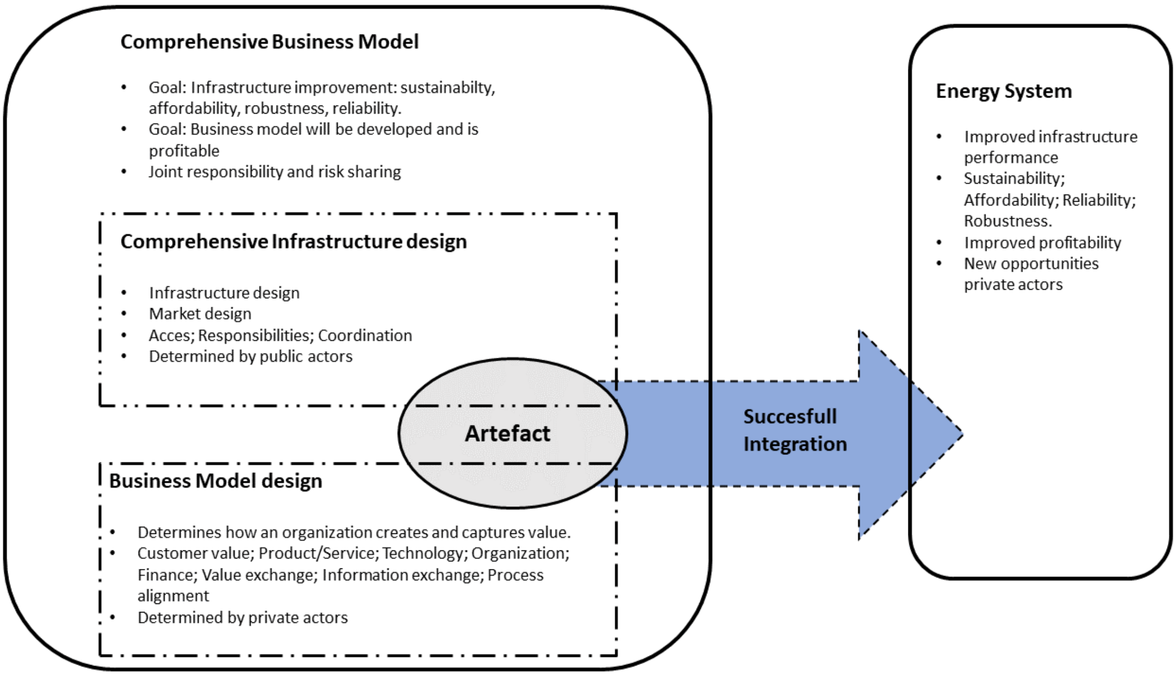

Figure 7. Conceptual model for the process of Comprehensive Business Modelling

2.4 Operationalization

2.4.1 Business model design construct

The business model design construct assists in the process of assessing the integration of a hydrogen business model by clarifying performance measure boundaries and the typology of the performance metrics. The metrics presented in the following table are constructed by adapting the business model metrics as defined by Heikkilä et al. (2016) to the H-vision project. Metrics are classified according to the components of existing business model ontologies, such as the CANVAS model, and extending them by including network-based activity elements, as discussed in table 3. Additionally, the metrics can be related to certain themes as they were found in specific literature. The factors have been tested against expert scrutiny, the interviews are presented in Appendix 2.

Factors	Metrics	Theme metrics
1. Customer value	Total amount of CO_2 emissions reduction	*C1. Created customer value*
	Acceleration of the energy transition	
	Hydrogen economy development	*C2. Market segment and market share*
	Potential to be a solution for niche problems	
2. Product/Service	Development time of new installations (phasing) & Lifetime of assets	*S1. Product/Service Development life cycles*
	Purity of delivered hydrogen	*S2. Quality*
	Reliability (On-time & quantity) of hydrogen shipments to consumers	
	Stakeholders support product/service	*S3. Satisfaction*
	Customer retention	
3. Technology	Hydrogen production and CO_2 capture	*T1. Architectural complexity*
	Hydrogen transport and storage	
	Power generation with Hydrogen	
	High-temperature heat generation with hydrogen	
	Modifications to existing assets to accommodate hydrogen as an energy carrier	
	Complementary technologies needed	
	Circular/modular design (flexibility of system)	
	% cross-system collaboration	*T2. Interoperability*
	Availability and downtime	*T3. Accessibility and Up-Time*
	Disaster recovery	
4. Organization	# of collaborating partners • tier 1: core network • tier 2: replaceable supplier/customer • tier 3: partners based on market availability	*O1. Collaboration*
	# of organizational layers involved	
	Roles and responsibilities	
	Access to supply chain network (suppliers etc)	

	Access to internal and external resources (tangible)	*O2. Access to resources*
	Level of centralization	*O3. Characteristics of Network*
	Ownership of assets within the project	
5. Finance	Value created by producing blue hydrogen in relation to alternatives	*F1. Network value*
	Profitability metrics such as: ROI; IRR; NPV; EPS; net profit; profit margin; turnover; revenue (growth); return on equity; cash flow; share price; project profitability; time to break even.	*F2. Profitability*
	Cost metrics such as: total expenses; CAPEX; OPEX, development costs; investment in technology; marketing costs; operational costs/loss; cost efficiency; fixed cost investment; cost control	*F3. Costs*
	# number of critical risks that can disrupt the project.	*F4. Risk*
6. Value exchange	# of partners involved in value exchange (transactions)	*V1. Number of partners*
	Value exchange (contracts) between upstream and downstream suppliers and customers	*V2. Value exchange between partners*
	Value attributed to resource and capabilities shared and exchanged within and between organizations.	*V3. Value attributed to*
	Dependencies, risk sharing, trust and commitment within collaborating organizations	*V4. Value conflicts*
7. Information exchange	# of partners involved in data, information and knowledge exchange.	*I1. Number of partners*
	Level of knowledge and information exchange (internal & external)	*I2. Data exchange*
	# of shared information systems; # of dedicated contact persons	*I3. Information accessibility.*
	Additional knowledge development to increase efficiency/profitability within project	*I4. Knowledge development*
8. Process alignment	Process throughput (process flow)	*P1. Process quality*
	Process standardization throughout the system	

Table 6. Factors for the design of business model within the hydrogen economy.

2.4.2 Technical system and Market design construct

The technical system and market design construct assist in the process of assessing the level to which the energy system is hospitable for the integration of hydrogen as an energy carrier. The metrics presented in the following table are constructed by adapting the comprehensive framework for the design of energy infrastructures presented by Scholten & Künneke (2016) on the Dutch energy system with the inclusion of hydrogen. Metrics are classified according to the layers of system design and economic institutions for energy infrastructures. The layers on the first level, informal institutions and technological feasibility, were not incorporated as they are on a different level of analysis and are less relevant to this research. The layers on the fourth level, system activities and market activities, are not incorporated in this design construct but are part of the business model construct. Additionally, the metrics can be related to the bridging themes in the comprehensive design framework. Access (A), interdependency between the first factors; Responsibilities (R), interdependency between the second factors; Coordination (C), interdependency between the third factors.

2.4.2.1 System design

Factors	Metrics	Theme metrics
1. Design perspective	(de)centralized level of production	*A1. System architecture*
	Interdependency of gas and electricity network	
	Hydrogen resources & production	*A2. Asset characteristics*
	Hydrogen transport	
	Hydrogen storage	
	End-use applications	
2. Design principles	Locations of Resources & production	*R1. Network typology*
	Locations of hydrogen (pipelines if applicable)	
	Locations of storage	
	Locations of end-users	
	Amount of hydrogen production needed (GW)	*R2. Production, grid and storage capacity*
	Amount of hydrogen grid capacity needed (GW)	
	Amount of storage capacity needed (GW)	
	Level of redundancy planning	*R3. Redundancy planning*
	Ownership of hydrogen production	*R4. Ownership and decisions rights*
	Ownership of hydrogen transport	
	Ownership of hydrogen storage	
	Ownership of hydrogen end-use	
3. Control mechanisms	Balancing regime (DSOs & GTS)	*C1. Operational coordination*
	Risk mitigation and prevention	*C2. Routines & emergency procedures*
	Safety instructions and standards	*C3. Preventive maintenance*

Table 7. Factors for the design of the technical system in a hydrogen economy.

2.4.2.2 Market design

Factors	Metrics	Theme metrics
1. Formal institutions	Government vision	*A1. Polity, judiciary, bureaucracy*
	Speed of government policy making	
	Anti-competitive behavior regulation	*A2. Competition law*
2. Governance	Degree of Liberalization	*R1. Degree of competition and unbundling*
	Level of unbundling	
	Structure of ownership for hydrogen production	*R2. Private vs. public ownership*
	Structure of ownership for hydrogen transport	
	Structure of ownership for hydrogen storage	
	Access regulation of hydrogen production	*R3. Regulation of access*
	Access regulation of hydrogen transport	
	Access regulation of hydrogen distribution	
	Access regulation of hydrogen storage	
	Tariff structure hydrogen	*R4. Energy tariffs*

	Tariff structure natural gas	
	Tariff structure carbon dioxide	
	Gas quality standard	*R5. Industry standards*
<u>3. Organization</u>	Contracts for differences in costs	*C1. Contractual arrangements*
	Roles of gas and electricity system operators	*C2. Degree of horizontal and vertical integration*
	Institutions enabling low transaction costs	*C3. Transaction costs*
	Energy or gas codes for hydrogen	*C4. Principal-agent and opportunistic behavior safeguards*
	Oversight	

Table 8. Factors for the design of the market in a hydrogen economy.

2.4.3 Project-System Performance construct

The project-system performance construct enables measuring the performance of the project in combination with the energy system in question. It consists out of four main factors: sustainability; affordability; system robustness; and reliability of operations. Each factor can be measured with two metrics. These metrics are in turn comprised out of a combination of theme metrics. For every of these theme metrics there should be an apt design in place in order to create an acceptable value for the metric and consequently contribute to a satisfactory value of the factor for project-system performance. For instance, if the theme metrics: C1 & T1 of business model design; A2 of infrastructure design are missing or poorly represented. The score for the metric 'level of decarbonization' will not be high, which in turn has a detrimental effect on the factor 'Sustainability' of the project and the energy system. Consequently, this has a detrimental effect on the performance of the prospective project and the energy system. In essence my argument is that when a project and system are designed well and in a symbiotic manner, additional value is created, and thus the design should be executed.

Factors	**Metrics**	**Comprised of design constructs theme metrics**		
		BM-D	I-D	M-D
1. Sustainability	Level of decarbonization	C1; C2; T1;	A2; R2	A1
	Acceptability and support for product/service	O1; O2; O3; S1; S2; S3; F1; I1; I2; I3; I4;	R1; R3; R4; C2; C3	A2; R1; R2; R3; C4
2. Affordability	Price of energy, project & system change	F1; F2; F3	A2	R4
	Distribution of costs and benefits Case	C1; C2; F1; F2; F3; F4; V1; V2; V3; V4;	A1; A2; R1; R4	R2; R4; C1; C3
3. System & Project Robustness	Level of Energy security	O1; O2; P1	A2; R2; C1	A1; C2
	Resilience of the project and system (Flexibility)	T1; T2; O3; P1;	A1; A2; R2; R3; C1; C2; C3	R3; R5; C2
4. Reliability of Operations	Availability of energy	S2; S3; T1; T2; T3; O2	R1; R2; C1	A2; R3; R5; C4
	Lifetime & performance of system components	S1; O3; P1	A2; C1	R5

Table 9. Factors for the performance of the energy system.

2.5 APPLICATION

In order to execute this case study analysis, the following protocol will be used. At first, the Dutch energy system will be briefly explained to provide overarching context as to what the situation is now. Then, for the purpose of data generation the scope of the H-vision project along with the three business options will be explained in detail. Finally, the chapter three will conclude with three possible designs for market and infrastructure that the government could choose upon.

Accordingly, in chapter four the framework will be applied. Data on H-vision, the market and the infrastructure will be analyzed to determine the nature and presence of the factors that make up each block. The results will be verified by interviewing experts that are situated in the energy sector or related fields. A 3X3 matrix should be the result, as every business model is matched with each technical system & market design. However, due to the time constraint of this thesis project only three combinations will be made. Low case business model with minimal adjustments in system and market design; Medium case business model with proactive adjustments in system and market design; high case business model with visionary adjustments in system and market design.

By analyzing these combinations, we can discern the effect of developing the H-vision project and specific policy has on the performance of the energy system. Upon this basis we can discuss what might be a desirable design for the Dutch energy system for the integration and adoption of hydrogen as an energy carrier.

3 H-VISION BUSINESS MODELS AND SYSTEM DESIGNS

In this chapter important background information is provided to understand the setting in which H-vision will be integrated. The chapter starts with the Port of Rotterdam and the role H-vision is to play. The current situation in the Port of Rotterdam will be covered to put the H-vision project in perspective. This is followed by the explanation of the three business model options for H-vision. The next sub-chapter covers the Dutch energy system to provide a general understanding of the system as it is now. Especially the gas transportation system is explained since this part of the energy system is relevant for the integration of (blue) hydrogen in the Netherlands. This is followed by the three system designs.

3.1 THREE BUSINESS MODEL OPTIONS H-VISION

A large part of the Dutch industry & energy sector is situated in the Port of Rotterdam. Covering an area of 12643 hectares the Port of Rotterdam harbors, 5 oil refineries, 45 chemical factories, 5 biofuel factories, 2 coal plants and couple of varying electricity plants. The Port of Rotterdam had a total energy balance of 7520 PJ incoming, 6790 PJ outgoing, 520 PJ of bunker storage, 60 PJ of stock fuel, and a consumption of 370 PJ of energy (Melieste, 2017). This consumption of energy results in annual CO_2 emissions of approximately 18.6 megaton (Kimkes & van ’t Wiel, 2019). Roughly 120 PJ of energy is used to generate electricity and the remaining 250 PJ is used to generate heat to catalytically reform oil. The refineries produce approximately 9.4 Mtons of CO_2, and constitute for 74% of the emissions of all the refineries in the Netherlands (Breij, 2018; Plomp, Barry, Kroon, McAlpine, & Mozaffarian, 2015; Römgens & Dams, 2018). The total amount of electricity producing capacity in the Port of Rotterdam is 6,500 MW, of which 3,500 MW are filled by gas plants, renewables, and combined heat & power plants (van Wijk, Rhee, Reijerkerk, Hellinga, & Lucas, 2019). The remaining 3,000 MW are produced in coal plants which, as stated in the previous section, will be prohibited in 2030. The energy and feedstock for industry in Rotterdam is mainly transported through an intricate pipeline network, approximately 1500km in length.

Since hydrogen as an energy carrier is viable pathway towards decarbonization in the Netherlands. It is, next to electrification, being seriously considered as an option for decarbonization in the Port of Rotterdam. There are several reasons why hydrogen as an energy carrier makes sense for the Port of Rotterdam. The first being that the Port of Rotterdam is no stranger in handling industrial gasses such as hydrogen. Half of the total Dutch hydrogen production and consumption takes place in the Port of Rotterdam. This means that there is already a small hydrogen infrastructure in place, two pipelines who are both operated and maintained by the companies Air Liquide and Air products. The second reason is that the Port of Rotterdam is an important import and export hub for energy in the Netherlands. With a yearly import of roughly 7,700 PJ and yearly export of 6,800 PJ in the Port of Rotterdam it facilitates 80% of the Dutch energy trade (van Wijk et al., 2019). Most of this energy, approximately 80-90%, is in the form oil or oil products. If the Port of Rotterdam wants to maintain its unique role in the energy trade it will need to start investing in methods to transport sustainable energy. Preferably in energy carriers that will have a prominent role in future national energy systems. Hydrogen appears to become that prominent energy carrier. Hydrogen can be stored and transported in various ways, with the most used techniques being: compression, cryo-genic liquification, nitrogen-based and toluene-based.

3.1.1 Minimal option

The minimal option is characterized by minimal adjustments to the participating refineries and power plants. Natural gas and/or refinery fuel gas is processed in a single ATR reformer plant. The required oxygen for reformation is supplied with a new dedicated oxygen plant. This option assumes that the total peak hydrogen demand constitutes 1183 MW. This demand is made up of: preheating the turbines in two coal-fired power plants (407 MW); replacing 25% of the natural gas used in a combined heat and power plant (143 MW); replacement of refinery fuel gas used in two refineries (500 MW); and replacement of imported natural gas to balance the grid within the refineries (90 MW). This would require a reformer plant with a capacity of 1036 MW to supply the necessary hydrogen. The reformer can run on 110% of its capacity to fulfil peak demand for hydrogen, this implies that no hydrogen storage is needed. The ATR plant has a minimum CO_2 capturing rate of 88%, leading to a 2.2 Mtpa CO_2 captured resulting in 27 Mton of CO_2 avoided during the entire project. A new local pipeline will be constructed to facilitate the hydrogen transport. The production of hydrogen will be ramped up during the first five years of the H-vision development. The CAPEX costs would be €1300 million, with a fixed annual OPEX of €18 million. This results in an avoidance costs of €190 per ton CO_2. Depreciating the revenue stream for present value over the entire project, which is scheduled to be until 2045, leads to an NPV of €-1,3 billion at a WACC of 3%.

3.1.2 Medium option

The medium option is characterized by serious adjustments to the participating refineries and power plants. The hydrogen will be produced in three ATR reformer plants by reforming natural gas and/or refinery fuel gas. The expected hydrogen demand is 3206 MW. This demand is made up of: firing the turbines in two coal-fired power plants and full integration with existing boilers (1611 MW); replacing 50% of the natural gas used in a combined heat and power plant (286 MW); replacement of refinery fuel gas used in two refineries (1170 MW); and replacement of imported natural gas to balance the fuel gas grid within the refineries (140 MW). Which will require a total reforming capacity of at least 2915 MW. Like the minimal option, production will be ramped up during the first five years, a new oxygen plant will supply the oxygen required in the reformation process, and the reformers can run on 110% capacity to meet peak demand. In this medium option however, the minimal capture rate is expected to be 88%, effectively capturing 5.5 Mtpa of CO_2 and avoiding a total of 79 Mton of CO_2 emissions during the project. Hydrogen transport will be facilitated through a local pipeline, additionally line packing will increase short-term flexibility. The CAPEX costs would be €3110 million, with a fixed annual OPEX of €43 million. This results in an avoidance costs of €146 per ton CO_2. Depreciating the revenue stream for present value over the entire project, which is scheduled to be until 2045, leads to an NPV of €-700 million at a WACC of 3%.

3.1.3 Maximum option

The maximum option is characterized by the maximal amount of adjustments to the participating refineries and power plants. Additionally, adjustments will be made to various installations of external natural gas users in the Port of Rotterdam area. The hydrogen will be produced in ATR reformer plants, the feedstock will be natural gas and/or refinery fuel gas. The expected demand is 5280 MW. This demand stems from: firing the turbines in two coal-fired power plants, full integration with existing boilers, and 15% hydrogen firing for the preheating of boiling feed water (2221 MW); replacing 100% of the natural gas used in a combined heat and power plant (571 MW); maximum replacement of refinery fuel gas used in two refineries (1170 MW); and replacement of imported natural gas to balance the fuel gas grid within the refineries (140 MW); replacement of refinery fuel gas used in two external refineries (600MW); replacement of natural gas by additional users (500MW). What makes this option different is that the storage of hydrogen is included. Hydrogen will be stored in underground salt caverns in Groningen. Because storage provides 1000 MW of flexibility, the total flexibility required in production capacity is much less. This leads to a required reformer production capacity of approximately 3820 MW hydrogen LHV, if storage is not possible a reformer production capacity of 4729 MW is necessary. Like the minimal and medium option, production will be ramped up during the first five years, a new oxygen plant will supply the oxygen required in the reformation process, and the reformers can run on 110% capacity to meet peak demand. The expected CO_2 capture rate as the ATR is 88%, leading to a 9.4 Mtpa of CO_2 captured and a 130 Mton in CO_2 emissions avoided during the entire project. The hydrogen transport will be facilitated by a new dedicate pipeline network, locally and nationally. The CAPEX costs would be €4260 million, with a fixed annual OPEX of €63 million. This results in an avoidance costs of €151 per ton CO_2. Depreciating the revenue stream for present value over the entire project, which is scheduled to be until 2045, leads to a NPV of €-2.1 billion at a WACC of 3%. For an overview of the hydrogen demand and production specifications in the H-vision project I refer to appendix 4.

3.2 Three System Designs

This sub chapter attempts to give an overview of the current Dutch energy system and plots the three system designs which we will work with in this research.

The total Dutch primary energy consumption in the year 2016 was 3155 PJ, see figure 8. About two thirds of this consumption is produced in the Netherlands, the rest is imported. The Netherlands imports 1275 PJ of primary energy and exports 9559 PJ. To generate electricity mostly natural gas and coal are used in gas or coal plants. Most of these plants are situated near the sea or a river due to the necessity for cooling water. Due to new climate goals the share of renewables in the electricity production has been increasing over the years. The expectation is that in 2030 around 47 GW of renewables will be installed in the Netherlands (Gasunie, 2018), putting additional requirements on the electricity grid due to their intermittent nature. This can be seen as a change in the broader landscape which in turn puts pressure on existing regimes in the energy sector to change, creating a window of opportunity for the hydrogen economy to emerge and become part of existing regimes (Schot & Geels, 2008).

The Dutch natural gas transport network consists of 15500 km of pipe, 19 mixing stations, 93 measuring and regulating stations, 22 compressor stations, 1300 gas receiving stations and 14 export stations (Vogel, Luiijf, Maas, Dijkema, & Zielstra, 2014). To transport gas over short distance no compressing is necessary due to gas being produced at approximately 80 bars. However, to transport natural gas over longer distances various compressors stations are needed to pressurize the natural gas. In the gas receiving stations natural gas out of the main transport network is depressurized in order for it to be used by end users through the regional networks. The main transport network is operated by Gas Transport Services, and the regional networks are operated by seven different organizations. For the network typology of gas, I refer to appendix 3.2. Due to the nature of gas in the largest explored gas field in the Netherlands the transportation network is divided. The first part transports gas of low calorific value and the other part transports gas of high calorific value.

The gas found in Slochteren is of low calorific value due to a 14% share of nitrogen in the gas. This natural gas is used mainly for low heat application, such as the heat demand for the built environment. High-intensive processes in industry and electricity generation require high-calorific natural gas. For these applications a special network is installed, certain firms that require large amounts of high calorific gas are connected to the main gas transport network operated by GasUnie Transport Services. The Netherlands extracts high calorific gas from the North Sea and is an important exporter and transporter of this gas to the rest of Europe.

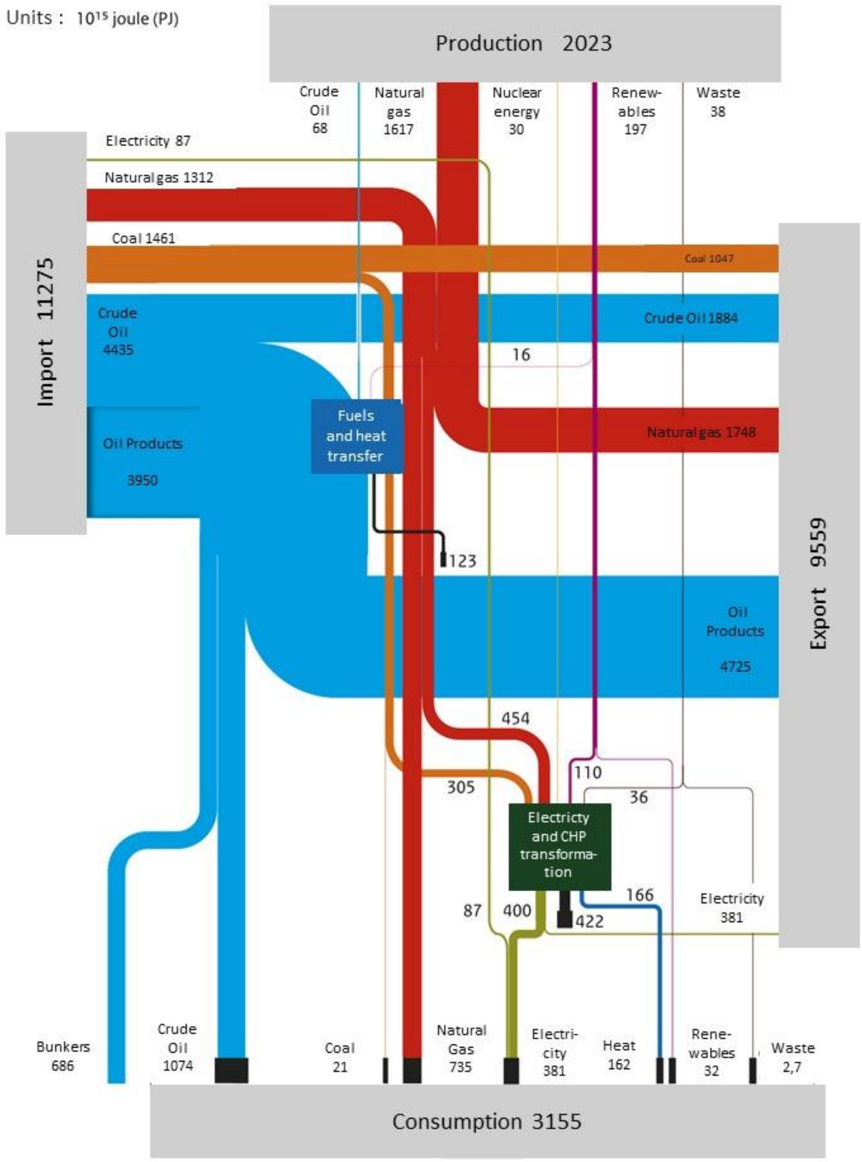

Figure 8. Sankey diagram of the primary energy flows in the Dutch energy system, year 2016. (adapted from Rijksoverheid, 2018).

The Netherlands has strict laws on any form of power abuse in the market. The Dutch Competition Act prohibits: unfair pricing, creating unfair trading conditions, and curbing production or technological development. The enforcement of this act however becomes difficult when dealing with networks. Networks have natural monopolistic characteristics, and even in liberalized markets can distort market functioning, particularly concerning energy companies (Künneke & Fens, 2007). Therefore, European governments decided to start liberalizing the energy production and energy sales. Consumers within the European Union were now able to choose their supplier. This enabled and stimulated energy trade within the European Union. The Dutch government implemented the Dutch Electricity and Gas Acts. Key features of these acts are the privatization of the energy market and the unbundling of energy supply and production from not only transmission network operations but also distribution system operators. This was argued to create a free energy market with more competition, leading to cheaper energy and better service. Overall leading to an increase in the protection of consumers.

3.2.1.1 Dutch Gas Transportation Network Operation

The Dutch gas transport network is operated nationally as previously mentioned by Gasunie Transport Services (GTS). This company is appointed by the Dutch government to maintain the capacity, balance and quality of the main transport network. GTS is a subsidiary of Gasunie. It transports the gas to gas receiving stations where the regional gas transport networks operator's takeover. These regional operators are: Coteq Netbeheer, Enduris, Enexis, Liander, Rendo Netwerken, Stedin, Westland Infra. Only parties that have a contract with GTS are allowed to transport gas along the network, program responsible parties. Usually these parties are also the Gas shippers that offer gas contracts to the consumers. The traders must have a contract with GTS, only then are they allowed to contract an amount of gas for transport to the consumer. They have a responsibility to maintain the balance in the supply system and deliver the natural gas to the consumer as agreed. The traders pay for the amount of gas extracted from the network and for the costs made by GTS to transport the natural gas. Only a small number of bulk consumers are directly connected to the main transport network. Usually these companies also have their own contracts with GTS. If one of the program responsible parties causes an imbalance in the network, GTS will compensate this imbalance and charge the blameworthy party with costs incurred.

Production of natural gas was approximately 80 billion cubic meters annually, however was drastically changed due to societal protest concerning gas production in Groningen. Since 2013 the annual gas production has decreased by almost 50%, to approximately 45 billion cubic meters in 2016. In the year 2016, 40 million cubic meters of natural gas was imported and 54 million cubic meters was exported (CBS, 2017). In 2018 a total of 939 TWh (96.1 billion cubic meters) was transported through the GTS networks to end users in the Netherlands and abroad (GasUnie, 2018). Because of the lower production of low calorific gas, GTS had to increase the use of its converters. In these converters high calorific gas is infused with nitrogen to create low calorific gas. The required capacity is set in order to deliver the necessary peak loads, these peaks take place when the mean effective 24-hour temperature is -9 °C or lower. Overall it is expected that the capacity demand in the Netherlands will slowly decline up to 2035, as presented in figure 9. The gas act states that the system operators must prove their ability to adequately transport natural gas, once every two years to the Dutch regulator.

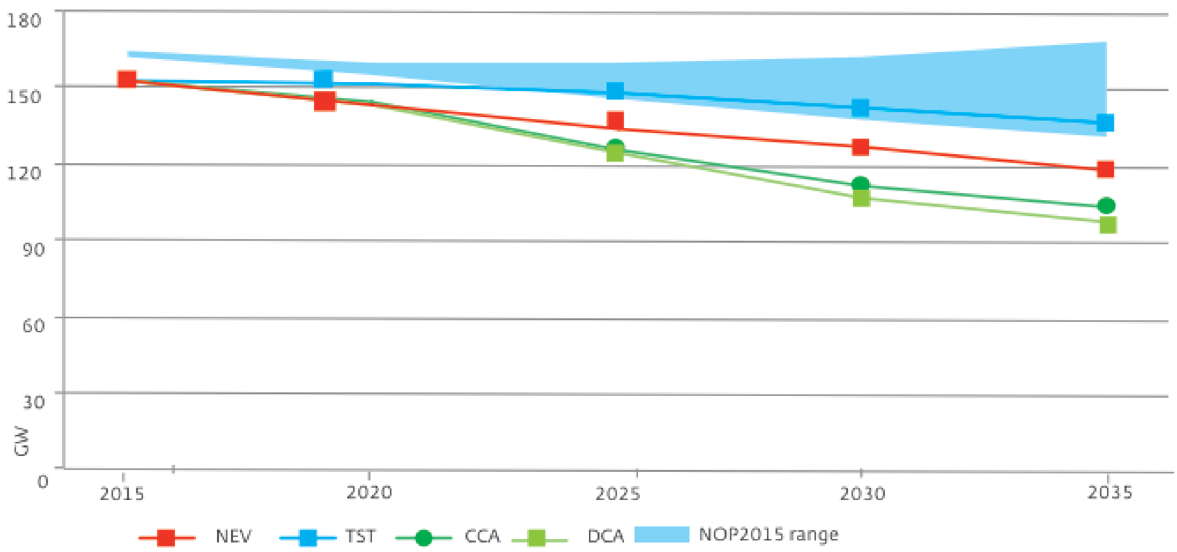

Figure 9. Forecasted capacity demand in the Netherlands according to four scenarios. Adopted from: Gasunie Transport Services, 2017.

The gas infrastructure grid consists of a wide variety of stations and components to control the gas flows throughout the network. Practically all these components follow the N+1 redundancy criterion. This redundancy criterion ensures the availability of the network in the event of an individual component failure. All components thus have a least one independent backup component. Concerning the storage of natural gas, the Netherlands has five large-scale underground gas storage facilities and multiple small- to mid- scale bunker storage systems. Table 10 provides details on the six largest operational natural gas storage facilities.

Storage facility	Operator	Type	Capacity working gas (million m^3)	Peak injection (million m^3 / day)	Peak extraction (million m^3 / day)
Norg	NAM	Depleted gas reservoir	7000	96	45
Bergermeer	TAQA Energy	Depleted gas reservoir	4100	-	-
Grijpskerk	NAM	Depleted gas reservoir	2000	61	16
Alkmaar	TAQA Energy	Depleted gas reservoir	500	32	3,6
Zuidwending	GasUnie	Salt cavern	310	43,2	26,4
Maasvlakte	GasUnie	LNG Bunker facility	78	31	0,25

Table 10. Overview of six largest natural gas storage facilities. Adopted from: International Energy Agency (2014).

3.2.1.2 Dutch Gas Transportation Network Ownership

Ownership of the Dutch gas infrastructure network varies along different segments, presented in figure 10. This is largely influenced by the third energy package which contains the unbundling regulation of the Dutch energy infrastructure. The third energy package and thus the degree of ownership in the Dutch natural gas value chain is determined by the Dutch government. The Dutch independent regulator checks if these mandates are adequately complied to. The exploitation of natural gas in the production segment is open for all producers on under strict regulations to ensure safety and sustainability of natural gas extraction. The producers work on a license-based scheme that is drafted by the ministry of Economic Affairs and Climate Policy. The transmission segment is fully owned by GTS and no competition is present. GTS is the transmission system operator and is legally and functionally unbundled from the rest of the segments. GTS issues contracts for traders to access the wholesale market, which is strictly regulated to enable transparency, automation and standardization. The wholesale market is a competitive market where producers offer their natural gas, traders compete for transport of natural gas, and consumers bid for their natural gas demand. The storage segment is regulated in the same manner as the production segment, in order to develop and operate a storage facility a license is needed which is provided by the Dutch government. Within the distribution segment a form of geographic regulated competition is present, allocation of property rights of the natural gas grid provides the distribution system operators to maintain and optimize the network while staying competitive. The distribution system operators are legally and functional unbundled as they are not allowed to produce, transmit or store natural gas.

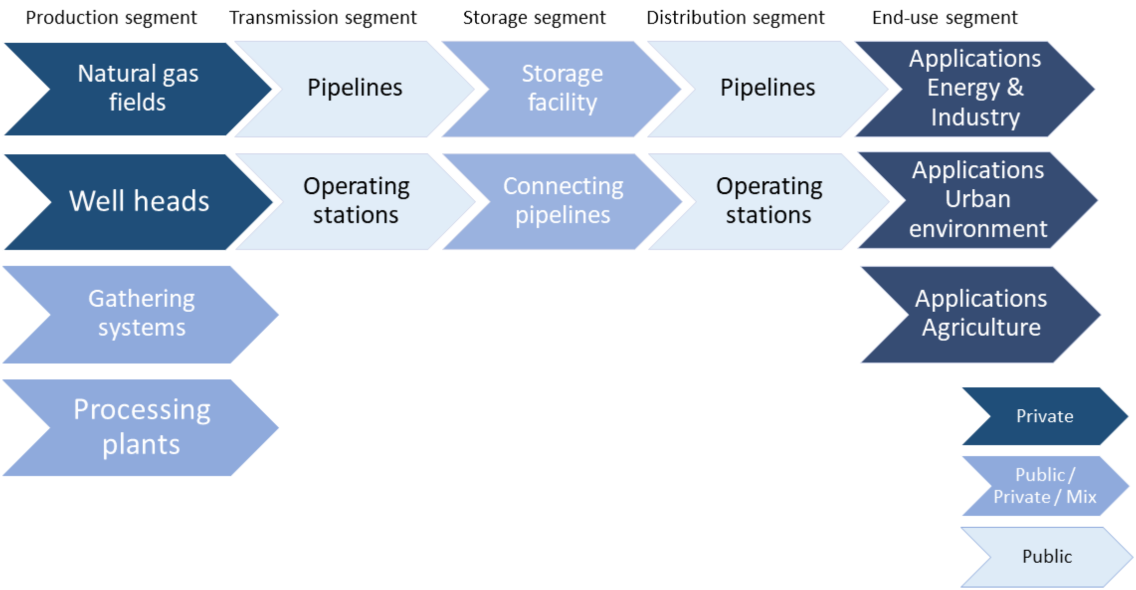

Figure 10. Ownership value chain natural gas in the Dutch energy system.

The natural gas price is determined by several different costs that are incurred by actors throughout the value chain. These costs are: the production costs, the international and domestic transport costs, storage costs, distribution costs. These costs together with a trading margin and tax on annual gas demand make up the natural gas price. The natural gas is traded in the spot market and needs to be nominated, which implies that the traders need to declare the hourly quantities of natural gas that is traded and needs to be transported to specific network points. The spot market is in essence a platform that enables GTS, producers, distributors, traders, and industrial end-users to synchronize their activities. Further cooperation concerns the industry standards, which are conducted on the regional, national and international level. These standards are in place to ensure competitiveness, safety, sustainability and further mitigation of negative externalities.

There are three general directions the government can take regarding the development of the Dutch energy system in relation to the integration of hydrogen. It can facilitate the development of H-vision, providing subsidy or tax exempts. Taking a more indirect approach and leaving the further development of the hydrogen economy up to the private sector.

The government can also facilitate the development of H-vision and invest in a national hydrogen infrastructure, i.e. a hydrogen backbone. Partially adjusting the current Dutch gas infrastructure. Taking a more hands on approach to the development of the hydrogen economy but leaving the specific direction up to the private sector.

The last system design is that of taking on the role of 'market shaper', creating a clear vision on the future of the Dutch hydrogen economy. These system designs embody the system effects. A change in the system design is the result of actions undertaken by actors in the system.

3.2.2 H-vision standalone

In this scenario the government provides the H-vision project with the bare minimum of financial support to develop the project. However, it doesn't take any further action on designing the system and market. This means that in there will be no public hydrogen infrastructure. Also, no regulation will be developed for hydrogen as an energy carrier. In effect the government takes the position of market 'fixer'. The government continues with investing in skills and science, providing a strong legal framework, supporting entrepreneurial clusters. The governments assumption is that the private sector will create an efficient market through the incentive of the profit motive. The government will only interfere on the 'coordination' level of infrastructure design to ensure proper conduct.

3.2.3 H-vision with hydrogen backbone

In this scenario the government closes the financial gap that is present in the H-vision project with adequate subsidy levels and tax exempts. Hydrogen will be used within industry to generate heat, and all industry hubs will require continuous large shipments of hydrogen. The government recognizes that if the private sector is left to its own devices a market failure is likely to occur within the new hydrogen economy, especially with the transport and storage of hydrogen. Because of scale economies the government regards the hydrogen infrastructure as a natural monopoly. The capital costs of pipelines are high, but large quantities can be transported with relatively low operation costs. This increases the risk for non-competitive behavior, which will decrease the establishment of competition. Therefore, in this scenario the government will provide the infrastructure required for the transport and storage of hydrogen, i.e. the hydrogen backbone. This hydrogen backbone is to be developed by Gasunie and will connect all large industry hubs. Concerning regulation, hydrogen must be ratified as an energy carrier and third-party access for actors that wish to access this infrastructure must be guaranteed. This will enable the development of a hydrogen exchange. The government will thus mainly interfere on the 'coordination' and 'responsibilities' level of infrastructure design.

3.2.4 H-vision with hydrogen economy development

In this scenario the government supports the H-vision project, develops a hydrogen backbone and makes creates a clear vision for the use of hydrogen in the energy system. This vision entails that industry must use hydrogen for their heat generation; all electricity plants will function as a back-up for intermittent renewable energy sources and must be CO_2 free by 2050; the city district heating plants will use hydrogen to generate their heat normally produced by fossil fuels. Subsidy concerning the stimulation of sustainable energy production will be broadened to support the production of blue and green hydrogen. The government will, on top of the actions previously mentioned, need to: commission further hydrogen projects, oversee the commercialization process of hydrogen as an energy carrier, help create institutions for the wholesale and retail market of hydrogen. This scenario sees the government as an active risk taker, with the ability to set the vision and mission for private sector growth within the hydrogen economy. Ensuring a balance between 'collective' distribution of risk taking in the innovation process and, a fair distribution of rewards. The government will take part in designing the energy infrastructure on all levels: 'coordination', 'responsibilities', and 'access'.

3.3 COMBINING THE BUSINESS MODEL WITH INFRASTRUCTURE DESIGN

The combination of the three business model options with the three infrastructure design scenarios will enable the determination of which comprehensive business model will lead to successful integration. It also enables the determination of the specific system effects on the performance of the business model. Since actions taken in in the design of either design construct has consequences in the other design construct. When perfectly applying this framework within a 3x3 matrix, nine combinations are possible, as presented in table 11.

	Minimal	**Medium**	**Maximum**
Standalone			
Hydrogen Backbone			
Hydrogen Economy Development			

Table 11. Combinations of Business model design and system design.

However, due to the time constraint of this research only three combinations will be made. The 'Minimal' business model option combined with the 'Standalone' system design. The 'Medium' business model option with the 'Hydrogen Backbone' system design. The 'Maximum' business model option combined with the 'Hydrogen Economy Development' system design. The choice for these three is that they are the three most like combinations to occur. If both the public and private actors lack vision and determination, the first combination will most certainly ensue. Simply put, the argument is that the level of reciprocal commitment determines the scale of the comprehensive business model. The first combination is in essence business as usual and will be used as the null hypothesis. The remaining two combinations are situations where system effects are actually present.

4 ANALYSIS

In this chapter the three combinations between the business model and infrastructure designs are made. Then, the performance of the combinations will be evaluated and compared. Finally, the performance of the framework will be assessed to answer the research question. Each combination starts with the business model and ends with its specific system design. In the first combination all the eight business model factors are covered. The second and third combinations only contain the adjustments to the first business model. Thus, in these combinations only the business model factors that contain different values are described. This choice was made since variance in the three business models is primarily given by their difference in scale. The system design in the first combination only covers the factors that are of importance when interfering within the coordination level. The second system design covers an increased number of factors due to the government taking more responsibilities. The third system design covers all factors mirroring the dedicated involvement of the government. These system designs incorporate the system effects of integrating H-vision into the Dutch energy system.

4.1 COMBINATION 1: MINIMAL BUSINESS MODEL - STANDALONE

4.1.1 Minimal Business Case

Customer value

The H-vision project uses the business model canvas to create a comprehensive overview of the value creation and capture process. The building blocks that are used in the CANVAS for the H-vision project are: the value proposition, key risks, key partners & value chain, structure and ownership, role of the government, cost structure, and revenue streams. Two building blocks, that are included in the CANVAS theory, customer segment and customer relationships, are not assessed in the CANVAS made for the H-vision project. Because the customers for blue hydrogen are included in the project development and considered to be key partners.

The value proposition is presented along five core values. The first being that H-vision will provide a *Mton-scale CO_2 emission reduction*. The H-vision project aims to for a 2 megatons per annum reduction in 2025 and a 6 megatons per annum in 2030. The second value is that H-vision will provide an *acceleration of the energy transition*. This reduction in CO_2 emissions will allow the Netherlands to reach the targets set by the Dutch government in order to adhere to the climate agreements for 2030. These targets are currently expected to not be met. The third value is H-vision will provide the *solution for high-temperature firing in the industry*. The high-temperature processes, temperatures over 800 °C, within industry are very difficult to decarbonize. This difficulty only increases for firing in the petrochemical and chemical industries since they currently, next to natural gas, also use industrial gasses that are the products of processes in these industries. The fourth value is that H-vision can pave the way for the *transition pathway to the hydrogen economy*. The development of H-vision according to the consortia should be seen as a stepping stone to the Dutch hydrogen economy of the future. In this future hydrogen economy solely, green hydrogen is produced and consumed. H-vision will enable the parallel development of hydrogen demand and supply. Creating a hydrogen market and equally important, an infrastructure for hydrogen. The fifth value is that the H-vision project can *reuse existing assets*. The assets currently in place in the Port of Rotterdam such as the refineries and chemical sites are already in place, and only need a limited amount of modifications.

The minimal case captures 2.2 Mtpa CO_2 annually whereas the total CO_2 emissions in the Port of Rotterdam are 18.6 Mtpa CO_2 annually in 2018 (Kimkes & van ’t Wiel, 2019). This would mean that the H-vision project reduces total CO_2 emissions by 12% in the Port of Rotterdam. The Dutch CO_2 emissions in 2017 were once again equal to 1990 levels (CBS, 2018), we might assume that this 12% reduction of emissions is relative to the 1990 level of emissions. This percentage is below the 40% defined by the Paris climate agreement. The H-vision project on this scale will remain a niche project and will not significantly accelerate the energy transition in the Netherlands. Electricity plants and refineries in the Port of Rotterdam will still use fossil fuels in the majority of their production processes. Created customer value is thus limited.

The H-vision project however does present a large step towards the development of the hydrogen economy. Even in the minimal case which requires a 1081 MW reformer. A reformer on this scale would be the largest production plant of hydrogen in the world. The biggest reformer to date is built in Texas and has a capacity of 330 MW (Air Products, 2018). Building the 1081MW reformer plant will lead to the generation of knowledge concerning the production of hydrogen. Which subsequently can be applied to future hydrogen projects in the Netherlands. H-vision also provides the sole solution, next to post-combustion carbon capture and storage, for decarbonizing the use of refinery fuel gasses. These gasses are by-products that form in the process of refining oil into high grade fuels. The refinery fuel gasses are re-used in the same refining process for producing heat, leading to large amounts of CO_2 emissions. Within the H-vision project the refinery fuel gasses are diverted from the refineries to the reformer plant and used in the production of hydrogen. At the reformer the CO_2 is captured, and the hydrogen is then transported back to the refineries and substitutes the refinery fuel gasses. The investments towards post-combustion carbon capture and storage can be seen has highly locked-in costs. These installations can’t be used for any other purpose but to capture CO_2 emissions at the specific refinery it is built. Investments in the H-vision project, in effect a pre-combustion carbon capture and storage method, can be spread over multiple hydrogen use cases. For the theme metric market share and market segment this business model case scores high.

Product/Service

The operating lifetime of the project is 20 years, starting with the first hydrogen production installation to be operational in 2026 until the decommissioning of the project in 2046. CAPEX is spread over the first three years of building the installations (2022-2025). For the refineries the hydrogen will be gradually phased in, and gradually phased out. It is assumed within all business model cases that 50% of the total capacity will be provided for with hydrogen in 2026, increasing with 10%/year, until 100% of the refinery furnaces are fired with hydrogen in 2030. Maintenance stops are planned years ahead in the refineries. These maintenance stops provide the opportunity to carry out furnace modifications. The development time and lifetime of assets are as to be expected from projects within the industry and energy sector. Additionally, this project will be able to contribute towards the decarbonisation goals as stated in the climate agreement. The service lifetime cycle is thus at an acceptable level.

The purity of hydrogen in the outlet stream of the ATR will be 95.5%. This purity is high enough for the presumed use cases in the refineries and power plants. The reliability of shipments is extremely important for the refinery use cases. Refining is a continuous process, shut down to insufficient supply are accompanied with extreme costs. All the business model options are designed in order to guarantee continuation of operations. The level of Quality in the project is high. On the topic of customer retention little can be found in the H-vision business model. This is due to the fact that the customers of hydrogen are in this case also partially the project developers. Moreover, within the energy and industry sector it is virtually impossible to make quick changes in assets and switch to another energy carrier. Due to path dependency customer retention is more or less a given.

Technology

Hydrogen production is done with by using a high-pressure Auto-Thermal Reformer (ATR). Relative to other reforming technologies it has by far the highest capacity per train and thus the best economies of scale. This results a big reduction in CAPEX due to the large scale of H-vision. Moreover, ATRs have demonstrated almost a perfect reliability of operation, with a 99.7% recorded availability in mega-methanol plants. ATR has a broad operating range (30-110% of capacity), and a high flexibility (1.5% of its capacity/minute). A high-pressure ATR is capable of producing hydrogen from a mixture of natural gas with refinery fuel gas with a fairly simple pre-treatment of the refinery fuel gas. This pre-treatment is standard technology for reforming plants and will not increase CAPEX significantly (less than 5%). Carbon capture at the ATR will be done by using the Rectisol physical absorption technology. The choice for this technology was done due to lower expected CAPEX and a higher energy efficiency. Within this business case, a single ATR train will be developed with a output capacity of 1040 MW hydrogen LHV (H-Vision, 2019).

Within the business model options only transport by pipeline has been incorporate in the design. This choice was made due to the scale of the project resulting that transport by truck or rail would not be able to support the volumes necessary at a cost-effective price. The pipeline diameter can be calculated as a function of the hydrogen flowrate, initial pressure, temperature and flow speed. A calculation was done by using a tool developed by TNO with a velocity of 15 m/s, presented in figure 11 below. The hydrogen delivery network required in the Port of Rotterdam is small enough to not require additional recompression for final use.

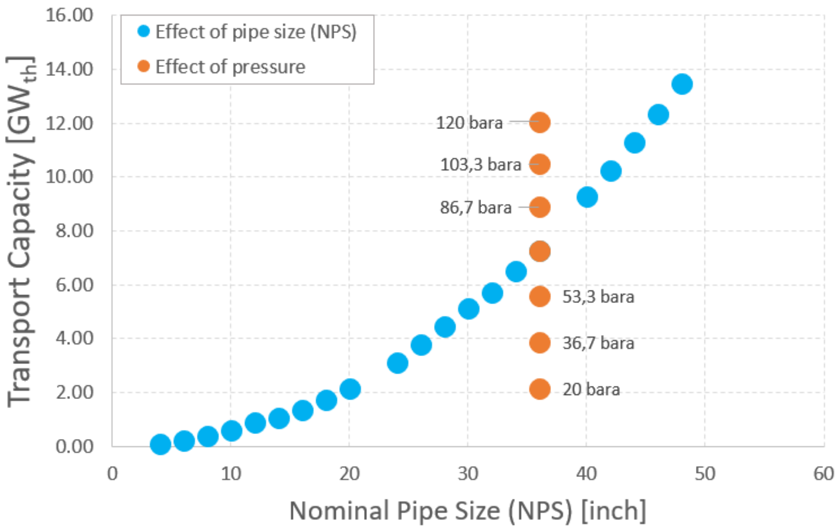

Figure 11. H_2 transport capacity of a pipeline in GW thermal, using LHV for H_2 (H-Vision, 2019).

Power generation by using hydrogen will be done by preheating the turbines in two coal-fired power plants. This requires the replacement or adjustment of burners in the boiler and a rearrangement of the heat exchangers in the boiler. The ATR also produces large amounts of excess steam which in the current circular design is used to generate electricity in the two nearby power plants. The power plants have enough capacity in their condensate systems to handle the streams produced by the ATR. This electricity is led back to the ATR for use in the air separation unit to produce oxygen, overall the ATR is still a net power importer plant. This design does however reduce costs significantly.

Most modifications to existing assets will be necessary within the refineries where the furnaces, fuel grids and flue gas stacks need to be modified to be able to support hydrogen as an energy carrier. The low estimate for both the BP and Shell Pernis refinery is 250 MW. The furnaces will be modified in a predetermined sequential manner. In order to maintain a continuous operation a separate distribution network is needed to supply blue H_2 to the furnaces that have been upgraded, shown in figure 12 below. Overall the architectural complexity is very high, but this falls within the range of skill that the collaborating partners have and is thus adequately incorporated in the design of the business model options.

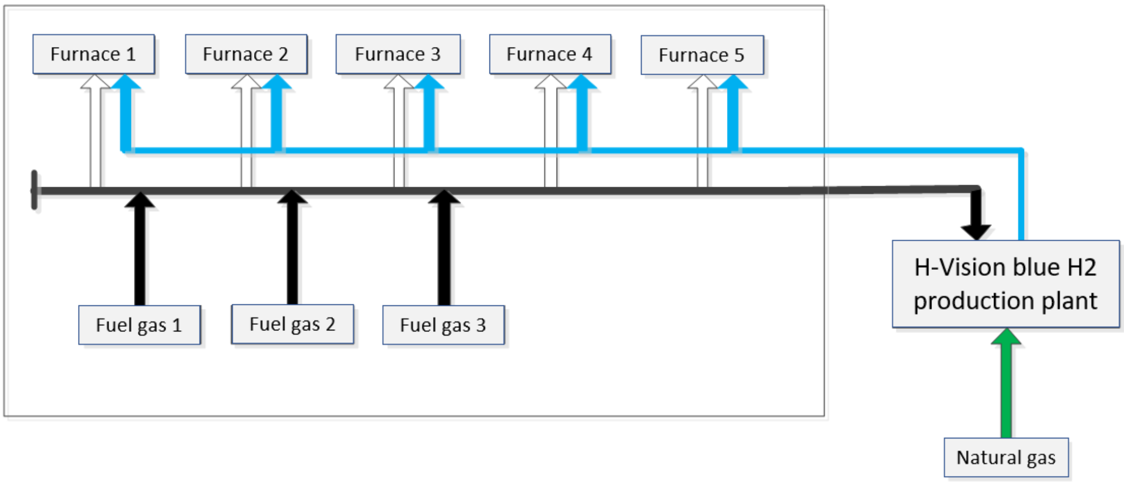

Figure 12. The proposed way to integrate the H-Vision concept within existing fuel gas grids (H-Vision, 2019).

Interoperability is a major part of the business model. In order to create economies of scale a multitude of varying and independent systems need to operate jointly. A high percentage of cross-system collaboration along the value chain needs to be achieved for the project to avoid disasters and downtime. The degree of accessibility and up-time is mainly covered in the risk assessment of the entire project and is not specific to a single business model option. Technical access to blue hydrogen in the business model options is in essence unlimited, it is possible to connect all actors to the hydrogen distribution network in the Port of Rotterdam.

Organization

The key partners are currently: Equinor, AirLiquide, Uniper, Shell, BP, ExxonMobil, Vopak, Gasunie and the Port of Rotterdam. For each of the partners the key drivers are that they can decarbonize their current activities and generate new business in hydrogen. The partners also recognize that there are two main critical issues that when are not solved will lead to the failure of the project. The partners require a security of supply, especially the refineries since the financial consequences of stopping the refinery process are vast. Additionally, the partners require economic feasibility of the project in order for it to not harm their competitive position in case the support it. Table 12 below shows the key partners for the minimal case. The core network partners (tier 1) are the partners that are willing or able to produce the hydrogen and at least another crucial role within the value chain. In this case these partners are: AirLiquide, Uniper, Shell, & BP. I argue that the Port of Rotterdam, EBN, and Gasunie are core network partner as well since they facilitate the transport and storage of CO_2, without the links in the value chain there is no 'blue' hydrogen. The evacuation of CO_2 is a structured as both public and private. The main route considered for the evacuation of CO_2 is by using PORTHOS. PORTHOS is a project jointly developed by EBN, Gasunie and the Port of Rotterdam. This project will transport and store the captured CO_2 in empty gas fields in the North Sea. Then there are two replaceable suppliers and/or customers (tier 2). These are: Equinor and Engie. Equinor supplies the natural gas that will be reformed into hydrogen and Engie solely a customer which can be replaced.

Key partner role:	Example for H-Vision:	Supply NG	Supply refinery fuel gas	Supply oxygen	Production H2	Transport H2	Storage H2	End-use H2 power plant	End-use H2 refinery	End-use H2 chemical sites	End-use H2 other sites	Transport CO_2	Storage CO_2
Natural gas supplier (wholesaler)	Equinor												
Industrial gas supplier	AirLiquide												
Power plant operator	Uniper												
Power plant operator	Engie												
Refinery plant operator	Shell												
Chemical industry operator	Shell												
Refinery plant operator	BP												
CO_2 transport and storage supplier	Port of Rotterdam, Gasunie &EBN												
			No activity				Possible activity				Core activity		

Table 12. Partners and their roles in the value chain for the minimal case.

As for the operation of H-vision, there will likely be 4 operational layers involved.

1. <u>Steering Board</u>

   Role: Ultimate decision-making body of the cooperation

   Members: Senior Management level from core network partners plus the Project Manager;

   Meeting frequency: 1 - 2 meetings per year during the life-time of the project.

   General Responsibilities: Endorsement of the project; Provide strategic directions to the Project (including next steps to be taken within the scope, planning and budget agreed between the Participants); Members shall act as ambassadors for the Project by their advocacy in their respective networks.

2. <u>Participants Board</u>
   Role: Management of the overall progress and quality of the project
   Members: Senior Management level from all the partners plus the Project Manager;
   Meeting frequency: Every 2 months or as required
   General Responsibilities: Appoint the Project Management Team and replacement of members of the Team; Ensure availability of necessary resources; Approve Project Plan and changes thereto; Entry of late Participants and the applicable Late Participants Fee; Evaluate the progress and results of the project; Review business models; Decide on a Participants request to leave the cooperation; Terminate the participation of a defaulting Participant; Any other key decision relating to the project.

3. <u>Project Management Team</u>
   Role: Day-to day management and execution of the Pre-Pilot Study
   Members: Chairs of the respective Work packages plus a Financial Controller;
   Meeting frequency: as appropriate but at least once per month;
   General Responsibilities: Manage overall progress and quality; Coordination and synchronization between Work package activities; Propose changes to the Project Plan; Make key decisions to the execution of a Work Package within the scope of their mandate; Embark on negotiations with Dutch and European Authorities; Communications to relevant external stakeholders to obtain and maintain support.

4. <u>Work Packages</u>
   In the different Work packages, the relevant competences from the different Founders and, when needed, external advisors are brought together to address the specific questions and subjects allocated to each Work package. These subjects cover business, technology, market, CO_2 transport and storage, strategic stakeholder management, and general installments of assets.
   Role: Execution of decisions made by the project management team.
   Members: Staff representatives of different relevant partners; relevant project advisors.
   General Responsibilities: Develop relevant knowledge base in the work package area of responsibility; Develop the appropriate solutions in further detail complying to indicated milestones and deliverables set by the project management team.

Overall the collaboration between partners is decent and straight forward. Still a lot has to be figured out when the partners start with the development of the H-vision project in September of 2019. Especially concerning the access to resources within the collaborating network. At this moment nothing has been set in stone regarding this metric. The level of centralization within the project organization is high and can be labelled as a functional structure. This leads to high specialization, a clear chain of command, narrow spans of control, and high formalization. Ownership of assets has yet to be determined in the next phase of the project. Especially concerning the production unit for hydrogen, i.e. the autothermal reformer plant.

Finance

The finance aspect of the business model is considered by many to be the most important factor. The value by producing hydrogen lies in the decarbonization of high temperature firing of fossil fuels. Whilst gas produced out of biomass, green hydrogen, solid biomass or post combustion CCS are possible alternatives for high heat demand. They are limited due to the scale of supply required and they are not cost competition. In addition, blue hydrogen production can be used as an outlet for excess refinery fuel gases, which is not the case for the other de-carbonization alternatives. H-vision thus has a unique value proposition, it is the *only* option that can decarbonise the use of refinery fuel gasses. Network value is sufficient enough to warrant development of H-vision.

Within the business model a wide range of metrics are calculated to give comprehensive overview of the project economics. The cash flows were established by using a wide variety of input parameters, presented in appendix 5, and were used to calculate the main profitability metrics (H-Vision, 2019):

- Net Present Value (excluding and including subsidies), defined as the sum of the net cash in-outflows for the project discounted at a WACC of 3%. A WACC of 3% is used as the standard within the economic model since it is comparable in governmental cases and studies, a WACC is also used for calculations in the climate agreement (Nijpels, 2018; PBL, 2019b).
- Value Investment Ratio (excluding and including subsidies), defined as the present value of the future cash flows of the project, divided by the initial investments;
- Internal Rate of Return (excluding subsidies), defined as the WACC which should be used to get a NPV neutral project;

The main cost metrics are defined as CAPEX and OPEX which are used to calculate the total expenses for the H-vision project. In turn the total expenses can be used in tandem with various input parameters to calculate the main cost metrics:

- CO_2 avoidance costs (overall, and in both power production and oil refining), defined as the ratio between the discounted cashflows compared with a reference and CO_2 emission reduction in Mton, discounted with the WACC of 3%.
- Delta Levelized Cost of Energy (Δ LCOE, excluding and including subsidies), is the ratio between the discounted cashflows compared to a reference situation and the produced hydrogen, discounted by the WACC;
- The required subsidy to produce an NPV of €0, is calculated as a CAPEX subsidy and an OPEX subsidy. In the current economic model, a maximum of 30% CAPEX subsidy is used, the rest of the required subsidy is granted through OPEX subsidy.

There are in total ten critical risks are defined by the H-vision project management for the current development phase and the next development phase.

The critical risks as defined by H-vision project management for the current phase (Assess) are:

- gross underestimation of total CAPEX;
- changing economics during construction or lifetime of the H-vision project;
- level of emission reduction is not accepted by government;
- the public perceives hydrogen as not safe.

Two are financial in nature and the other two are technical/social in nature. The according mitigation actions are described as well. In order to make an accurate estimation of CAPEX the H-vision management team will use an appropriate cost break down structure, work with service/equipment suppliers, and incorporate an uncertainty range into the financial model. In order to mitigate risks of changing economics the management team will validate economic parameters, stress test the financial model against scenarios, advocate for government contracts, and passing through costs to clients or price indexing. In order to make sure that the government accepts the level of emission reduction the H-vision management team will liaise with the Dutch government as soon as possible. Adjusting the technical design to meet the necessary requirements. The public safety perception is difficult to mitigate, the main action is to prevent accidents that can harm the general safety profile of H-vision.

For the next phase (Select), the H-vision management team foreshadows six critical risks. These are:

- insufficient CO_2 transport and storage capacity;
- adverse macro-economics resulting in reduced blue hydrogen demand;
- internal rate of return of the project is deemed too high by the government and too low for the H-vision partners.
- Lack of commitment, project partners refuse to enter into long term commitments matching CAPEX depreciation;
- Insufficient project funding due to inadequate subsidy or policy instruments;
- Lacking interfaces, i.e. difficult cross chain integration leading to significant delays.

Four of these risks are financial in nature, one technical and the last organizational. There are quite a few critical risks, but there are not necessarily more present than in similar energy projects. Key is to create a strong strategy to mitigate these critical risks. Dealing with risk should and is an ongoing process which is executed by the project management team of H-vision.

Modelling this case gives the following results:

Metric	**Outcome**
Net present value excluding subsidies (in billion €)	- 1.8
CO_2 avoided (Mton)	27
Value investment ratio (VIR/Profitability index) including specified subsidies in the model	100%
Value investment ratio (VIR/Profitability index) excluding subsidies	-125%
Delta Levelized Cost of Energy (LCOE) excluding subsidies (€/MWh)	19.61
Avoidence costs relative to ETS-price (€/ton)	112.47
Avoidence costs absolute (€/ton)	**146**
Internal rate of return without subsidies (IRR)	≠
Internal rate of return including specified subsidies in the model (IRR)	3.0%
Total CAPEX (in billion €)	0.8
Required CAPEX subsidy (in billion €)	0.24
Required OPEX subsidy for first 15 years (€/ton avoided)	7.7

Table 13. Results economic model minimal case.

Value exchange

Concerning value exchange not much has been currently established in the 'Assess' phase of the project. This will most likely be set in stone in the 'select' phase of the project. Partners are still allowed to retreat from the project without incurring costs or paying a fine to the other partners. This already has resulted in negative effects. Social loafing has already been experienced within the development of the feasibility study in the current assess phase.

Information exchange
The core network partners all participate in information sharing, with addition of a number of knowledge firms such as TNO, Berenschot & Deltalinqs. Within the current phase the knowledge & data sharing is extensive, especially since the partners want to create a business model that is as realistic as possible. This indirectly leads to a significant development of knowledge [I4] that increases the efficiency/profitability of the project. There are a large number of experts working on the H-vision project. However, as I have witnessed the process of sharing knowledge and information is riddled with inefficiencies. There is no shared information system, everything is done by e-mail. Which very often leads to people losing important information or are even unaware of information due to non-sequential responsive behavior.

Process alignment
Currently the business model has not, in detail, covered the nature of all the process which need to be aligned among the partners. Currently, most of the capabilities shared among the core network partners is human capital. Their tacit knowledge and skills are used to establish the feasibility of the project.

4.1.2 H-vision standalone

***Market*: Organization**
Within this scenario the government only provides the H-vision partners with soft loans. These are loans with very low interest to stimulate investment. This is the most basic form of financial support the government can offer. This will be altered form of the current Energy Transition Financing Facility, i.e. ETFF, which will be granted by the governments investing branch: the Dutch Investing Agency.

***System*: Control mechanisms**
On the technical side the government only sets some requirements regarding control mechanisms to which the collaborating partners must adhere to. The government demands that H-vision is developed and operationalized with adequate attention to risk mitigation and prevention. The government also underlines the necessity of safety instructions and standards for preventive maintenance. This is done to ensure the safety of the Dutch citizens and reduce the chances of a disaster occurring. The specifics of these requirements are like that of current energy & industry projects. Requirements for production of hydrogen will most likely under supervision by the Inspection for Living Environment and Transport, i.e. ILT (Minsterie van waterstaat en infrastuctuur, 2019). Private parties create the infrastructure necessary for the transport of hydrogen. This will be a continuation of activities already performed by several private parties. Air Liquide operates a hydrogen pipeline network of approximately 1000 km between France, Belgium and the Port of Rotterdam in the Netherlands. Air products has a hydrogen pipeline network of approximately 140 km within the Port of Rotterdam area. The further development of the hydrogen infrastructure in this scenario is linked to private business cases and will be highly dependent on the (local) presence of producers and end-users.

4.2 COMBINATION 2: MEDIUM BUSINESS MODEL – HYDROGEN BACKBONE

As explained in the introduction of this chapter, only the business model factors that show significant change will be covered in combination 2 and combination 3. For the factor Product/Service no changes are to be found, the service lifetime cycle of the project remains the identical, the level of quality across the three business models stays the same, as well as the customer retention within the project. As for the factors value exchange and information exchange. In all three business models there is not a strong emphasis on these factors. However, as explained this could change in subsequent phases of the project.

4.2.1 Medium Case

Customer Value

The expected CO_2 capture rate of the reformer is slightly higher than the minimal option. In this medium option the capture rate is expected to be 90%, effectively capturing 5.5 Mtpa of CO_2 and avoiding a total of 49 Mton. This would mean a that the H-vision project reduces total CO_2 emissions by 30% in the Port of Rotterdam. This percentage is still below the 40% defined by the Paris climate agreement. So, the created customer value is higher than the minimal option but still not adequate for what the customers require. The second theme metric, market segment and market share, increases as well. Hydrogen as an energy carrier is used in an increased amount of processes executed by the collaborating partners. This leads to hydrogen taking a bigger share of the energy & industry energy demand.

Technology

The larger demand for hydrogen also requires an extra ATR train, totalling two ATR trains. This production unit will have a output capacity of 2920 MW hydrogen LHV (H-Vision, 2019). This would directly become by far the largest production unit of hydrogen anywhere in the world. This also comes with an more modifications to the installations owned by the collaborating partners. For the refineries the retrofitting of extra burners is not more challenging. To balance the fuel gas grid within the refineries with hydrogen gas requires some upgrades to certain compressors. This should not prove difficult. Overall, the two refineries have stated that they are able to execute the transformations. Now for the two coal plants within this case quite some new technologies are required. Hydrogen will be fired in two new gas turbines, which will be the MH701D gas turbines. Part of the flue gas will be mixed with the boilers air inlet system and a smaller part will be used to pre-heat boiler feed water. These modifications are more extensive than the first option, which increase the level of architectural complexity and costs.

Organization

Table 14 below shows the key partners for the medium case. This table is exactly the same as the table presented in the minimal case. The core network partners (tier 1) are still for the same reasons: AirLiquide, Uniper, Shell, BP, and the Port of Rotterdam. The two replaceable suppliers and/or customers (tier 2) are once again: Equinor and Engie. The reason for the unchanged organizational network is because these partners retrofit a larger part or all of their installations for use of hydrogen. As such the hydrogen demand increases to reach the capacity these partners have available. The other metrics are fulfilled identical to the minimal case.

Key partner role:	Example for H-Vision:	Supply NG	Supply refinery fuel gas	Supply oxygen	Production H2	Transport H2	Storage H2	End-use H2 power plant	End-use H2 refinery	End-use H2 chemical sites	End-use H2 other sites	Transport CO_2	Storage CO_2
Natural gas supplier (wholesaler)	Equinor	Core activity											
Industrial gas supplier	AirLiquide			Possible activity	Possible activity						Possible activity		
Power plant operator	Uniper				Possible activity			Core activity					
Power Plant operator	Engie							Core activity					
Refinery plant operator	Shell		Core activity		Possible activity				Core activity				
Chemical industry operator	Shell		Core activity		Possible activity					Core activity			
Refinery plant operator	BP		Core activity		Possible activity				Core activity				
CO_2 transport and storage supplier	Port of Rotterdam											Core activity	Core activity

No activity | Possible activity | Core activity

Table 14. Partners and their roles in the value chain for the medium case.

Finance

The same metrics are used, however due to larger CAPEX, OPEX, Tariffs, and Revenues the model produces different results.

Metric	Outcome
Net present value excluding subsidies (in billion €)	- 0.65
CO_2 abatement (Mton)	48.71
Value investment ratio (VIR/Profitability index) including specified subsidies in the model	100%
Value investment ratio (VIR/Profitability index) excluding subsidies	77%
Delta Levelized Cost of Energy (LCOE) excluding subsidies (€/MWh)	8.0
Avoidence costs relative to ETS-price (€/ton)	41
Avoidence costs absolute (€/ton)	**146**
Internal rate of return without subsidies (IRR)	1.1%
Internal rate of return including specified subsidies in the model (IRR)	3.0%
Total CAPEX (in billion €)	2.85
Required CAPEX subsidy (in billion €)	0.70
Required OPEX subsidy for first 15 years (€/ton avoided)	0.00

Table 15. Results economic model: medium case.

4.2.2 H-vision + Hydrogen backbone

Market: Governance

The degree of competition and unbundling will be similar for the most part of the hydrogen value chain. Except for the production segment, the government will liberalize this part of the value chain. The production of hydrogen in contrast with the production of natural gas does not require extensive mining activities. This lowers the barriers of entry to the production segment in the value chain. Increasing competition, boosting hydrogen economy development and reducing hydrogen prices. This includes system operators to be allowed to participate in the production of hydrogen gas. Currently, they are already involved in natural gas conversion activities. This will be done by a producer SMR and ATR technologies are technically gas conversion technologies, a logical step would be to use the expertise of the system operators. This might require a form of unbundling in order to maintain adequate performance levels, especially when hydrogen becomes an integral part of the energy system.

The hydrogen transmission network will be owned by public system operators. The costs for transforming parts of the current national gas transport network to transport hydrogen will be a fraction of the costs to build a new dedicated pipeline network. As such the private sector will never build a national network if this option can potentially be realized, if developed it would instantly make a private owned transmission network redundant. However, to stimulate hydrogen economy development small industrial hydrogen distribution networks will be allowed to be private. For instance, the hydrogen in the large industry hubs will be private and will be connected to the national transmission network, i.e. the hydrogen backbone. The owners of the distributing networks will ask a fair tariff for third parties to access these networks. By structuring the transport of hydrogen as such, the government benefits significantly with minimal costs. In the long term the government will need to acquire the hydrogen pipelines owned by private actors when all-inclusive access is necessary. Ownership of hydrogen storage will be regulated, but it can be structured in the same manner as the current natural gas storage structure. A combination of private and publicly owned storage facilities.

Trading on the market for hydrogen can be facilitated in a practically identical manner as trading in natural gas is being performed today, here I refer back to sections 3.1.2 and 3.1.3. The Title Transfer Facility (TTF) is a virtual trading point for natural gas in the Netherlands which allows gas to be traded within the Dutch gas transmission network. The TTF system is operated by Gasunie Transport Services, within the system wholesale gas is mainly traded off-exchange, directly between two parties, by inter-dealer brokers. Natural gas is metered in €/MWh. This system can be copied and applied to the hydrogen market, it will only be for accessible for Dutch traders.

The government will implement a tariff on the amount of CO_2 per ton. This will be hard minimum price independent from the European Emissions Trading system. Within this scenario the government will keep in line with its current focus. The energy transition must be cost efficient (Ministerie van Economische Zaken, 2016). The government will therefor implement a CO_2 base tariff of €12.30 in 2021 increasing to €31.90 in 2030 and €75.45 in 2050. This will be a base tariff excluding the ETS price, which is a slight altercation from a currently proposed plan (Rijksoverheid, 2019b). The government will implement this tariff in a uniform manner across all sectors. Current energy taxes on the consumption of electricity and natural gas will remain at the same level. The proceeds of the tariff and energy tax will entirely be made available as subsidies for the industry and electricity sector to stimulate emissions reducing measures through the subsidy for sustainable energy program (SDE++). This tariff structure results in the lowest social costs relative to other tariff structures (PBL, 2019a).

Market: Organization

Thus on the economical side the government helps with financing hydrogen projects through the SDE++ program (Ministerie van Economische Zaken en Klimaat, 2019; Navigant, 2019; PBL, 2019a). Either a CAPEX subsidy, an OPEX subsidy or a combination of both will be implemented. Most likely this will be by contributing a significant amount of cash, i.e. capex support, in the range of 10-30% of CAPEX. Additionally, an OPEX subsidy will be included which is based on the amount of avoided CO_2 emissions, this will be done by subsidizing the difference between the costs (€/ton CO_2 reduced) and the CO_2 tariff implemented. This subsidy scheme could see the government becoming a shareholder and partner of the H-vision project and other hydrogen projects. Additionally, this scheme works very well during construction and operations phases.

The current gas law and regulation will need to be adjusted to allow for a national hydrogen infrastructure. The Gas Act, the Mining Act, and the energy codes will need to permit the distribution of hydrogen through the publicly owned grids. Additionally, the gas laws and regulations need to be reformulated to contain clauses concerning the specifics of production, transportation, storage, and consumption of hydrogen. For instance, the purity of the hydrogen gas produced, transported, and consumed must be at least 95%. Requirements for production of hydrogen is supervised by the Inspection for Living Environment and Transport, i.e. ILT (Minsterie van waterstaat en infrastuctuur, 2019). The requirements for transport and use of hydrogen will be monitored by the State Supervision of Mines, i.e. SodM (Staatstoezicht op de Mijnen, 2019). Which at the moment supervises the extraction of natural gas and the storage of CO_2. Since blue hydrogen requires CCS, assigning this mandate to the SodM will increase network effects within policy forming and supervision of the hydrogen economy.

***System*: Design perspective**

As for the scenario where the government decides to develop a national hydrogen infrastructure. It will need to order Gasunie to split the current gas network into a hydrogen transmission network and a methane transmission network. The production of hydrogen will be centralized carried out within large steam methane reforming or auto thermal reforming plants. Hydrogen will only be used to decarbonize large segments of industrial and energy generating activities. The current high-calorific part of the gas network is connected to all large industry hubs, and to export and import points Assigning part of the high-calorific network to the transport of hydrogen will thus create the most value. This leaves the low calorific part of the gas network, which is connected to the domestic market via the low-pressure networks of the DSOs, to continue transport of methane gas. With this design all the existing end-user gas applications can still be used in the future. This will enable the transition to encounter less opposition especially in the domestic market. The adoption of hydrogen as an energy carrier in the domestic market will take longer due to the large number of actors, natural gas will slowly be phased out.

***System*: Design principles**

The pipes used in the Dutch high-calorific network are made of steel, which has proven to be able to safely and reliably transport hydrogen. Detailed calculations have shown that the current high-calorific network when transporting 100% hydrogen, with equal pressure, can transport 80% of the energy value in comparison with high-calorific natural gas (van den Noort, Sloterdijk, Vos, & Lieffering, 2017). This does however roughly require three times faster transport speeds, due to hydrogen having an energy density of approximately 12 MJ/Nm^3 and high-calorific gas having an energy density of 40 MJ/Nm^3. High velocities might lead to vibration or erosion problems. Vibrations might occur due to the characteristics of the pipeline geometry and density of the gas. The density of hydrogen is nine times smaller than natural gas which largely compensates the effect of higher velocities. On top of this a higher velocity is not necessarily a problem. In the Netherlands the criterium for maximum gas velocity is set at 20 m/s, in practice however it often is maintained at 10 m/s. The velocity limit is somewhat arbitrary, for instance in North-America the criterium for maximum gas velocity is set at 30 m/s (van den Noort et al., 2017). To prevent internal corrosion, it is essential to transport clean and dry gas. The relative humidity of the gas must under all circumstances be less than 60%.

Vibration, erosion and metal fatigue of pipes may lead to pipes rupturing. When a crack in the pipeline forms the gas exists the pipe at its maximum possible rate of expansion. Current natural gas pipelines must provide enough resistance to crack growth in order to stop the propagation of a crack within a limited pipe length. Fracture mechanics is an extensive field, so I will not go into detail but when a crack grows in a particular material, the material’s resistance to the fracture increases. For a steel gas pipe, it is essential that the decompression velocity of the gas is larger than the propagation velocity of the crack. Decompression velocity is related to the speed of sound in the transported gas. The speed of sound in hydrogen (1284 m/s) is three times larger than in natural gas (430 m/s). The higher decompression speed is a positive factor, which results in reduced chance of crack propagation. The conclusion is that the current high-calorific pipe network can be used for the transport of hydrogen. With a footnote that the pressure cycle must be adjusted to keep the amount of metal fatigue within operational boundaries and must be monitored for the presence of vibrations.

Hydrogen requires the compression of three times as much volume for the same energy value as for natural gas. Currently, two types of compressors are being used in the Dutch gas infrastructure, reciprocating and centrifugal compressors. The reciprocating compressors are able to compress hydrogen, especially at the amounts of pressure needed in the network. However, to compress hydrogen centrifugal compressors would need an 1.74 times increase in rotation speed (van den Noort et al., 2017). This rotation speed increases tension of the material of the compressor. The compressor is not designed to resist this level of tension and will break. All the centrifugal compressors will therefor need to be replaced. Since hydrogen does not decrease in temperature when decompressed, it even slightly increases in temperature. The pressure regulation stations are no longer necessary since heating of hydrogen gas is not necessary.

Storage will be jointly developed with the hydrogen backbone. This will be done by storing hydrogen in underground salt caverns. Hydrogen can be stored in underground salt caverns that originated from salt extraction. Salt is a fully gas tight material for most gasses, this includes hydrogen. Since the 1970s hydrogen has been stored in caverns, an example is Texas, USA (CE Delft, 2018). Another example is a cavern in operation with a working capacity of approximately 430 kWh/m^3 with 310 kWh/m^3 cushion gas. Hydrogen gas can be used as cushion gas, this ensures high purity. In comparison hydrogen storage in gas fields requires natural gas as a cushion gas. This complicates the extraction of hydrogen, natural gas and hydrogen mix to form a syngas. The salt caverns that will be used are located at Zuidwending. The cavern size will range from 600,000-1,000,000 m^3, at a depth of 1,000- 1,500 m. The minimum operating pressure will be between 80-84 bars, and the maximum operating pressure will be approximately 180 bars. Based on a 600,000 m^3 cavern the amount of cushion gas required is 156,000 MWh and the working gas will be 195,000 MWh. For such a cavern the withdrawal capacity is 18,000 MWh/day and the injection capacity is 19,500 MWh/day. This translates to a flexibility of 800 MW, based on the LHV of hydrogen. At the Zuidwending location there is room for 10 caverns. The estimated costs for the first cavern are €150-160 million to establish the necessary installations in the above ground facility. Every extra cavern would require an additional €35 million. The fixed OPEX costs for one system are expected to be €7 million/year. Every extra cavern increases this fixed OPEX costs by 2-3%. To connect the H-vision project with the storage facility 377 km of pipelines are necessary, 280 km of natural gas pipelines can be transformed to transport hydrogen within that corridor. This leaves approximately 100 km of hydrogen pipelines which will need to be developed. Regarding production, grid and storage capacity.

For the H-vision project the required buffer size is approximately 168 hours, which is effectively 1 week. A one-week storage buffer translates to, assuming the three business cases, between the 36.438 and 185,644 MWh. Which would exactly fit into one salt cavern. However, a recent estimation is that one third of the current Dutch primary energy consumption can be substituted by hydrogen (Melieste, 2017; TKI Nieuw Gas, 2018). In other words, roughly 1700 PJ or 472.22 TWh of hydrogen would need to be produced and transported annually. This is well within bounds of the current Dutch natural gas network capacity, which is 939 TWh annually (GasUnie, 2018). As previously mentioned, with the same pressure hydrogen can transport 80% of the energy value in comparison to natural gas. As such roughly 63% of the gas network would need to be transformed to sustain the maximum forecasted hydrogen demand. As for storage, only 100 PJ or 27.78 TWh of hydrogen will be used for electricity production (TKI Nieuw Gas, 2018). If we assume that a buffer of one week is required to maintain continuous operation, a buffer of 0.53 TWh is needed. This would roughly be equal to three 600,000 m^3 salt caverns. Extra production and storage facilities for hydrogen will need to be developed in this scenario, extra grid capacity however not. Network redundancy will be handled in an almost identical manner as it is being done right now with the natural gas network. Activities such as: patrols, smart pigging, leak detection, pipeline markers and gas sampling of the hydrogen pipeline network will be executed to detect and prevent defects.

Ownership of the assets in the hydrogen value chain and infrastructure can be mirrored to the ownership framework of the current Dutch natural gas infrastructure. With the exception being the production segment and the distribution segment as described in the market design. As presented in figure 13.

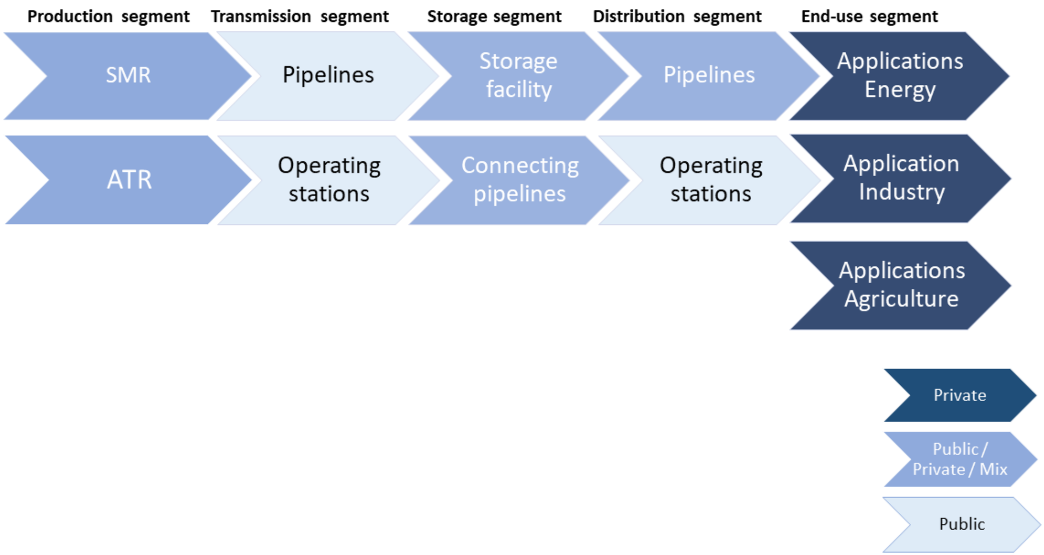

Figure 13. Ownership within the value chain of hydrogen gas in the Dutch energy system for hydrogen backbone system design.

System: Control mechanisms

As for the balancing regime the same program can be used as for the current natural gas network. Before the start of the gas day all shippers send their gas portfolios to Gasunie Transport Services showing the predicted hourly TTF deals, entries and exits for the following day. This data enables the determination of the Portfolio Imbalance Signal. The aggregate of all Portfolio Imbalance Signals is called the System Balance Signal. This System Balance signal is zero when the gas network is perfectly balanced, on both sides of the spectrum there is a small range in which imbalance is tolerated. Gasunie Transport services monitors the System Balance Signal and takes corrective action if necessary. As for safety standards and risk mitigation the same institutions can be used as mentioned in the previous combination, section 4.1.2.

4.3 Combination 3: Maximum Business Model – Hydrogen Economy Development

4.3.1 Maximum Business Case

Customer Value

The expected CO_2 capture rate of the reformer is as designed higher than the medium option. The expected CO_2 capture rate of the reformer is 94%, leading to a 9.4 Mtpa of CO_2 captured and a 130 Mton in CO_2 emissions avoided during the entire project. This would mean a that the H-vision project reduces total CO_2 emissions by 51% in the Port of Rotterdam. This percentage is above the 40% defined by the Paris climate agreement and even above the 49% goal set by the Dutch Government (Ministerie van Economische Zaken, 2016). The created customer value is much higher than the previous two options, and even slightly exceeds expectations of the customers. The second theme metric, market segment and market share shows an increase as well. Hydrogen as an energy carrier is used in an increased amount of processes executed by not only the collaborating partners but by actors outside of the scope of the business model as well. A bandwagon effect ensues, increasing the installed base and as a result complementary goods will be produced, perhaps by the collaborating partners. Further enforcing the adoption of hydrogen as an energy carrier in the Netherlands. Overall, leading to a bigger share of the Dutch energy consumption being fulfilled by hydrogen.

Technology

As for the maximum business case two ATR trains will be developed. The total output capacity of this unit will be 3820 MW of hydrogen at LHV. This capacity without storage would have to be 4820 MW but due to the incorporation of storage in underground storage facilities, this is not necessary. Transport to and from these facilities is expected to be made via the hydrogen backbone proposed by GasUnie. Within the current model the costs for transporting hydrogen on the hydrogen backbone are included. As well as the CAPEX costs for constructing one salt cavern, the costs are estimated to be €285 million.

Organization

Table 16 below shows the key partners for the medium case. This table is substantially larger than the table presented in the minimal and medium case. The core network partners (tier 1) are still: AirLiquide, Uniper, Shell, BP, and the Port of Rotterdam. The replaceable suppliers and/or customers (tier 2) are: Equinor, Engie, Exxon Mobil, Gunvor, Air Products, Huntsman, and LyondellBasell. Due to increased scale of hydrogen production and the hydrogen demand of the core network partners is fulfilled, capacity is available for use by other companies. Then there are two new partners which are based on market availability, Vopak & GasUnie. Due to the scale of the maximum case storage and transport of hydrogen are necessary and thus included in the business model. GasUnie has the skillset and capacity to support the entire transport and storage of hydrogen within the H-vision maximum case, while VOPAK does not.

Key partner role:	Example for H-Vision:	Supply NG	Supply refinery fuel gas	Supply oxygen	Production H2	Transport H2	Storage H2	End-use H2 power plant	End-use H2 refinery	End-use H2 chemical sites	End-use H2 other sites	Transport CO_2	Storage CO_2
Natural gas supplier (wholesaler)	Equinor												
Industrial gas supplier	AirLiquide												
Power plant operator	Uniper												
Power Plant operator	Engie												
Refinery plant operator	Shell												
Chemical industry operator	Shell												
Refinery plant operator	BP												
Other blue H2 off-takers	ExxonMobil												
Hydrogen storage service supplier	Vopak												
CO_2 transport and storage supplier	Port of Rotterdam												
Transmission system operator gas	GasUnie												
Refinery plant operator	Gunvor												
Industrial gas and chemical supplier	Air Products												
Chemical industry operator	Huntmans												
Chemical industry operator	LyondellBasell												
			No activity				Possible activity				Core activity		

Table 16. Partners and their roles in the value chain for the maximum case.

Finance

Modelling this case gives the following results.

Metric	Outcome
Net present value excluding subsidies (in billion €)	- 1.5
CO_2 abatement (Mton)	90.6
Value investment ratio (VIR/Profitability index) including specified subsidies in the model	100%
Value investment ratio (VIR/Profitability index) excluding subsidies	64%
Delta Levelized Cost of Energy (LCOE) excluding subsidies (€/MWh)	7.01
Avoidence costs relative to ETS-price (€/ton)	36.96
Avoidence costs absolute (€/ton)	**91**
Internal rate of return without subsidies (IRR)	0.1%
Internal rate of return including specified subsidies in the model (IRR)	3.0%
Total CAPEX (in billion €)	4.55
Required CAPEX subsidy (in billion €)	1.365
Required OPEX subsidy for first 15 years (€/ton avoided)	0.2

Table 17. Results economic maximum case.

4.3.2 Hydrogen economy development

***Market*: Formal institutions**

Important here is that the government has a clear vision of how it wants hydrogen to be used in the Dutch energy system. The government wants an energy system in which green hydrogen is produced on a large scale in combination with hydrogen storage to increase the efficiency of renewable energy sources. The government creates a clear policy for the production, transport, storage, and end-use of hydrogen. The government finds that blue hydrogen will be an important stepping stone to a green hydrogen economy and will subsidize the production of blue hydrogen it becomes independently cost competitive with fossil fuels. Green hydrogen production will be subsidized until it becomes independently cost competitive with blue hydrogen. Transport of hydrogen will be facilitated by public system operators. Storage of hydrogen will be done on a large scale and all the available salt caverns will be operationalized for hydrogen storage. The government mandates the use of hydrogen for heat generation in the industry, energy and urban environment sectors. Within the mobility sector it sets targets for the heavy transport, ships, trucks & busses, to use hydrogen as a fuel and for personal transport (cars) to use electricity as fuel. This policy creates clear boundaries for the private sector to operate in and reduces risks for large scale investments. The timeframe for this vision will be in concordance with the climate agreement, with major milestones for transformations of these sectors being set for 2030 and 2050. The government will also need to critically scrutinize any activities performed by incumbent actors to resist this change.

***Market*: Governance**

The government will liberalize the production segment of hydrogen as above ground facilities will be used to produce hydrogen. The government will maintain the same level of unbundling for the hydrogen transmission and distribution networks are for the current natural gas infrastructure. This means that both transmission and distribution of hydrogen will be executed by public system operators. The same structure of ownership in the transport and storage of hydrogen as currently in the natural gas market is necessary due to a large amount actor within the Dutch energy system requiring access to the hydrogen infrastructure in this combination.

Even more so than in the previous combination hydrogen there will be a necessity for trade of hydrogen across the Netherlands. The Title Transfer Facility will be implemented for hydrogen trading. A virtual trading point where hydrogen will be traded for €/MWh. A well performing trading platform will attract more traders with their own hydrogen stocks, increasing the security of hydrogen supply. Additionally, the platform enables a better synchronization of supply and demand which will keep the price competitive. This platform will be an integrated system, meaning that traders from all over Europe can trade on this platform. Apart from an interconnecting infrastructure which will be explained in the system design perspective. Hydrogen market integration requires adequate working market structures to ensure efficient and cost recovering usage. All wholesale suppliers registered in a E.U. member state must be sanctioned to supply any wholesale customer in another E.U. member state. With the prerequisite that this venture complies with trading, balancing rules, and security of supply requirements. To stimulate the integration customs duties and quantitative restrictions on the import and export of Hydrogen will be prohibited. This does not include restrictions or measures justified on grounds of public policy or public security, under the assumption that they do not comprise of disguised discriminations or restrictions. An integration made under these provisions will lead to the mutual recognition of licenses and a mutual reciprocity within the hydrogen market.

As for energy tariffs, the government will put a high tariff on CO_2 emissions, and it will not put a cap on the amount of CCS allowed. A CO_2 minimum price between the €90-165 per ton CO_2 emitted in 2030, results in a 50% chance for the Netherlands to achieve the goal of 14.3 Mton annual CO_2 reduction that was agreed upon in the climate agreement for the industry and energy sectors (McDonald, 2019; Nijpels, 2018). A minimum CO_2 tariff in this design will be set at €50 in 2021 and will increase in a linear fashion to €155 in 2050 which is in line with recommendations in the Dutch climate agreement (Rijksoverheid, 2019a). This tariff however will be a base tariff including the ETS price, in contrast with the previous combination. The proceeds from this tariff will be used to heavily subsidize the industry and energy sectors to decarbonize their activities. This tariff will be implemented on a nationwide level. Current energy taxes on the consumption of electricity and natural gas will remain at the same level until 2030. After 2030 the energy tax on natural gas will be increased in order make the production green hydrogen cost competitive with the production of blue hydrogen. The proceeds of the tariff and the energy tax will entirely be made available as subsidies for the industry and electricity sector to stimulate emissions reducing measures through the subsidy for sustainable energy program (SDE++). This tariff structure results in an increased level of welfare, a 0.6% increase, and has the biggest effect on CO_2 emission reduction in the Netherlands and the rest of Europe due to industry actors not allocating production to other countries (PBL, 2019a).

***Market*: Organization**

Within this system design the government is an active risk taker. It will ensure a balance in the distribution of risk taking in project development and ensure a fair distribution of rewards. As in the previous system design the government actively subsidizes hydrogen project through the SDE++ program (Ministerie van Economische Zaken en Klimaat, 2019; Navigant, 2019; PBL, 2019a).

The government needs to off-set risk somehow. A crucial metric for investors in all kinds of projects, and for that matter hydrogen projects, is the Weighted Average Cost of Capital (WACC). The WACC is what a business expects to return on a project. In the discounted cash flow analysis of a project the WACC can be applied as the discount rate for future cash flows in order to derive the projects net present value (NPV). If this NPV is negative investors will not deem a project worth pursuing. In other words, the WACC is the minimum acceptable rate of return at which a project needs to yield returns for its investors. The problem currently lies in the fact that the government can take more risk, this effectively lowers the WACC required for hydrogen projects, and consequently when modelling the finances of project derives a higher NPV and a lower financial gap. In contrast private investors are more risk averse, this effectively increases the WACC they require for hydrogen projects, and consequently when they model the finances of a project derive a lower NPV and a higher financial gap. The government can decrease risk for companies in a number of ways.

Government can off-set risks related to changing commodity prices which lead to companies being able to lower their WACC and consequently significantly reducing the financial gap. The ETS prices can be a main candidate for such a contract since it is a major financial risk within the economic model of blue hydrogen projects. The government can also partially or entirely compensate the marginal costs for producing blue hydrogen. Quite simply when the marginal revenue per kilogram hydrogen produced surpasses the marginal costs per kilogram hydrogen produced, the producer will earn a profit and vice versa the producer will incur a loss. A potent subsidy scheme for hydrogen projects that reduce CO_2 emissions. Is that the government guarantees to subsidize these projects in their first years up to the level that their marginal costs equal their marginal revenues. Ensuring that at the least these projects break even at their conception.

Similar to the last system design scenario the current gas law and regulation will need to be adjusted to allow for a national hydrogen infrastructure. For the specifics I refer back to section 4.2.2. Additionally, the degree of horizontal integration will increase as the roles of the gas and electricity operators get redefined and more cooperation is needed to balance the entire system.

***System*: Design perspective**

Green hydrogen production will rapidly develop and have a larger share of total hydrogen production. Electrolysis plants will be located close to renewable energy sources. As for the system architecture this entails that the level of production will be more decentralized and an increased level of interdependency between the gas and electricity network. This comes with additional system integration issues that will need to be investigated, but as explained are outside the scope of this research. The production of hydrogen will thus be increasingly decentralized and will be carried out within electrolysis plants and auto-thermal reforming plants combined with CCS. Steam methane reforming technology will not be used within this scenario as it is the most polluting technology for hydrogen production.

As per the governments vision hydrogen will be used for heat generation in almost all of the industrial processes; hydrogen will be used within all electricity plants to generate electricity when renewables are not able to cover demand; hydrogen will be used to heat the urban environment. A large part of the natural gas network will be transformed into a hydrogen gas network before 2050. Starting with the high-calorific natural gas transmission network, which will quickly be transformed into a hydrogen transmission network. The low-calorific natural gas transmission network and the natural gas distribution networks will be gradually transformed, mirroring the adoption of hydrogen as an energy carrier in the urban environment and mobility. To enable an integrated hydrogen market connection points with international hydrogen infrastructures. This can largely be done by copying the current natural gas infrastructure connections. A connection station will be placed at certain connection points, these connection station will transform the gas velocity, quality and pressure to match that in the national hydrogen transmission network.

***System*: Design principles**
As for the design principles, a lot of the principles mentioned in the previous system design will hold. The maximum gas velocity in the network needs to be 30 m/s. The network needs to be monitored for vibrations, erosion and metal fatigue. Network redundancy will be handled in an almost identical manner as it is being done right now with the natural gas network. Activities such as: patrols, smart pigging, leak detection, pipeline markers and gas sampling of the hydrogen pipeline network will be executed to detect and prevent defects.

In this system design half of the current Dutch primary energy consumption will be substituted by hydrogen (Melieste, 2017; TKI Nieuw Gas, 2018). In other words, roughly 2550 PJ or 807.33 TWh of hydrogen would need to be produced/imported and transported annually. The current Dutch natural gas network capacity is 939 TWh annually (GasUnie, 2018). As previously mentioned, with the same pressure hydrogen can transport 80% of the energy value in comparison to natural gas. Implying the entire natural gas network will need to eventually be transformed to support hydrogen transport, and at least 70 TWh of capacity needs to be added before 2050. As for hydrogen storage, 150 PJ or 41.67 TWh of hydrogen will be used for electricity production. If we assume that a buffer of one week is required to maintain continuous operation, a buffer of 0.80 TWh is needed. This would roughly be equal to four 600,000 m^3 salt caverns. Throughout all segments in the value chain infrastructure will need to be adapted or developed.

Ownership of the assets in the hydrogen value chain and infrastructure can be mirrored to the ownership framework of the current Dutch natural gas infrastructure. This reflects the dedicated approach by the government to develop the hydrogen economy and its infrastructure as mentioned in the market design section. As presented in figure 14.

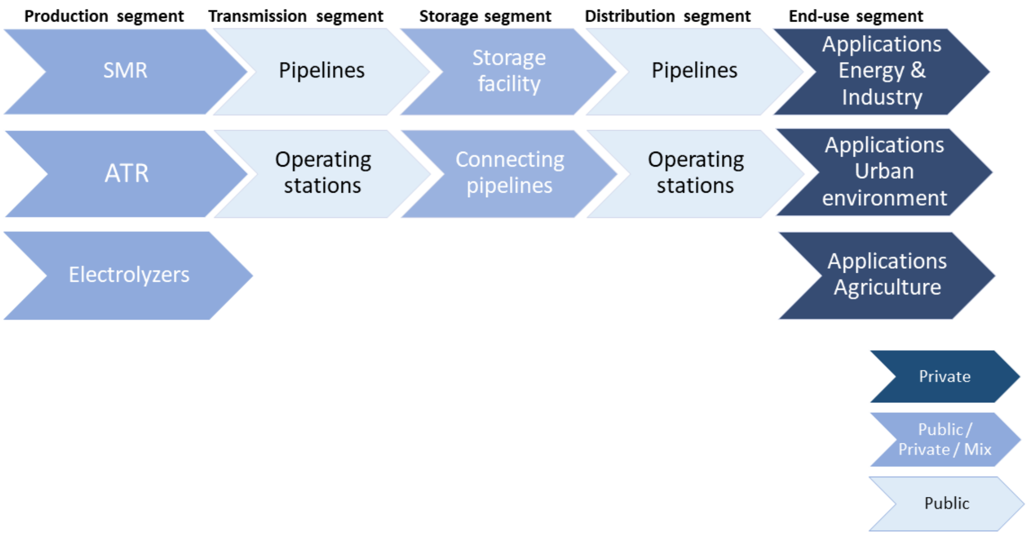

Figure 14. Ownership within the value chain of hydrogen gas in the Dutch energy system for hydrogen economy development system design.

***System*: Control mechanisms**

As for the balancing regime the new program will need to be established. The increased interdependence of both the electricity and gas network will require a slight adaption to the balancing regime to balance both networks. Green hydrogen plants are literally connecting both the gas and electricity network. However, green hydrogen production plants are extremely flexible in their production. Production levels of these plants can be virtually instantly modified between 0% and 100% of their capacity. The problem is situated in timing of communication by the shippers of electricity and the shippers of hydrogen gas. The shippers of electricity should communicate their predicted hourly TTF deals, entries and exits for the following day slightly earlier than the shippers of gas. This enables the operators of green hydrogen plants to establish their production level for the following day which they in turn can communicate to their shipper or Gasunie. In short due to the intermittent nature of renewable energy sources and profit motives the system balance signal for the electricity network must be established before that of the hydrogen gas network. As for safety standards and risk mitigation the same institutions can be used as mentioned in the previous combinations.

4.4 COMPARISON

4.4.1 Combination 1

The first combination is not very likely to be developed. The projects potential is lacking in a number of factors. The first being the sustainability of the project. This project will not hold up against alternatives in the amount of CO_2 emissions it reduces. More value can be created by making investments for decarbonizing industrial and electric generating activities with other technologies. Additionally, there is no incentive for industry and energy actors to change their activities since there is no CO_2 tariff. As for the affordability, the degree of profitability and opportunity for the private actors is nonexistent without subsidies. Although this combination would only need €240 million in CAPEX subsidy, which is 30% of the total CAPEX. This combination would require a very high OPEX subsidy of 7.7 €/t which the government will never agree to. This directly affects the affordability of the project. The price of energy (€/kg.H2) is too high, a large enough market cannot be created due to scale issues. Distribution of costs and benefits heavily skewered since costs dominate. As such the affordability of the project is very low.

The last two factors system robustness and reliability of operations are at acceptable levels. This is primarily due to the fact that the project is not integrated in a very complex system. It is rather an integration into the systems of a small number of private actors. The scale of this project only requires retrofitting small parts of their private systems. These actors' number eight in total and are also close in proximity to each other. The size of these systems and their close proximity increases the resilience of the system and the level of energy security. The availability of energy within the project is high as well, the main feedstock for the ATR is natural gas and syngas. Natural gas is provided by a large-scale supplier such as Equinor, but this is a tier 2 partner, meaning that Equinor is replaceable. In case of unsatisfactory supply, a different supplier can be chosen. Moreover, syngas is provided by the refineries themselves, which are tier 1 partners, meaning that their always will be a certain level of energy available to continue operations. Lifetime & performance of system components are fine. The estimated lifetime of the project is 20 years, system components are mostly proven technologies.

Factors	**Metrics**	**Comprised of design constructs theme metrics**		
		BM-D	I-D	M-D
1. Sustainability	Level of decarbonization	T1;		
	Acceptability and support for product/service	O1; O2; O3; S1; S2; S3; F1; I1; I2; I3; I4;	C2; C3	
2. Affordability	Price of energy, project & system change	F1; F3		
	Distribution of costs, benefits and risks	C1; C2; F1; F3; F4; V4;		
3. System robustness	Level of Energy security	O1; O2		C2
	Resilience of the energy system (Flexibility)	T1; T2; O3; P	C2; C3	C2
4. Reliability of Operations	Availability of energy	S2; T1; T2; T3; O2		
	Lifetime & performance of system components	S1; O3	C3	

Table 18. Factors for the performance of the system comprised of metrics incorporated in combination 1.

4.4.2 Combination 2

The second combination is the most likely to be developed, especially from the perspective of the private sector. The main reason is that the factor affordability scores high, and no major changes to current policy is necessary. With a CAPEX subsidy of 25% i.e. €700 million, the project would already have an acceptable value investment ratio (100%) and internal rate of return of (3%). With a combination of CAPEX and OPEX subsidy the government might even have to subsidize less. A rough calculation shows that if the government subsidizes €4.5/ton CO_2 avoided, a CAPEX subsidy of €300 million would be enough. A such distribution of costs, benefits and risks are acceptable for all parties involved, the price of energy remains high, but it is now at a level all investors are willing to pay. The sustainability of this combination is much better than the last combination. The level of decarbonization is moderate, 5.5 Mtpa captured implies a 30% reduction on the 18.6 Mtpa CO_2 emitted in the Port of Rotterdam. The goals in the climate agreement are 14.3 Mtpa reduction in the industry sector and a 20.2 Mtpa reduction in the energy sector. The business model in this combination only allows for a 16% progression towards achieving these goals. This has a slightly negative effect on the acceptability of the project. However, the support for hydrogen as an energy carrier is larger than in the previous combination. Stakeholders on the economic and technical side will implement new strategies and adjust their assets to support and incorporate hydrogen as an energy carrier in their activities.

System robustness has only slightly improved, the increased capacity for hydrogen transport will lead to the formation of a larger market for hydrogen. A larger transport capacity and market results in an increased level of resilience and energy security. However, the production of hydrogen will be done in only a few locations in the Netherlands. If for instance the ATR production unit in Rotterdam unexpectedly malfunctions there is no alternative for the supply of hydrogen within the Netherlands. The value for the factor reliability of operations remains rather similar, blue hydrogen will mainly be produced, natural gas will be used as feedstock, and the lifetime & performance are identical to the last combination. The factors affordability and sustainability, for both the project and the energy system, are at a level that allows for the development of this design. This combination can function as a good foundation upon which the hydrogen economy can be developed further.

Factors	**Metrics**	**Comprised of design constructs theme metrics**		
		BM-D	I-D	M-D
1. Sustainability	Level of decarbonization	C1; C2; T1;	A2; R2	
	Acceptability and support for product/service	O1; O2; O3; S1; S2; S3; F1; I1; I2; I3; I4;	R1; R3; R4; C2; C3	R1; R2; R3; C4
2. Affordability	Price of energy, project & system change	F1; F2; F3	A2	R4
	Distribution of costs, benefits and risks	C1; C2; F1; F2; F3; F4; V1; V2; V3; V4;	A2; R1; R4	R2; R4; C1; C3
3. System robustness	Level of Energy security	O1; O2	A2; R2; C1	C2
	Resilience of the energy system (Flexibility)	T1; T2; O3;	A2; R2; R3; C1; C2; C3	R3; R5; C2
4. Reliability of Operations	Availability of energy	S2; S3; T1; T2; T3; O2	R1; R2; C1	R3; R5; C4
	Lifetime & performance of system components	S1; O3; P1	A2; C1;	R5

Table 19. Factors for the performance of the system comprised of metrics incorporated in combination 2.

4.4.3 Combination 3

The third combination creates by far the most value for both the public and private sector. This combination scores high on the factor 'sustainability'. It is the only combination that achieves more than 40% reduction in current CO_2 emissions in the Port of Rotterdam. Additionally the business model for H-vision alone contributes to achieving 31% of the 34.5 Mtpa CO_2 reduction set in the climate agreement for the industry and energy sectors (Nijpels, 2018). In this combination hydrogen can truly become a prominent energy carrier due to wide spread support from both the public, the government and industry. Something that must be handled with the utmost care is maintenance and accidents. The adoption of hydrogen as an energy carrier can be upset suddenly if accidents are poorly managed, certain experts interviewed accentuated this as crucial for hydrogen integration into the energy system. This combination also scores high on system robustness and reliability of operations. The stimulation of additional hydrogen production in combination with an integrated hydrogen market increases energy security and availability. The increased size of the Dutch hydrogen market and infrastructure also increases the resilience of the energy system. As long as all assets are properly monitored for defects, it is likely that no major disruptions will occur within the hydrogen infrastructure.

The factor this combination does not score great on is Affordability. While it does have a better price for the hydrogen (€/kg) and levelized cost of energy (LCOE) in relation to the other combinations. The price tag for building such a large project and retrofitting infrastructure accordingly, are high. The scale of disruption this combination entails will encounter opposition from various sorts of stakeholders, effecting the acceptability. The affordability of the project could be improved by a better distribution of costs and benefits. In this combination the developers of H-vision included the cost for building hydrogen storage facilities into their business model. If hydrogen storage is developed by Gasunie, separate from the H-vision project the distribution of costs and benefits would improve significantly. For this combination four salt caverns for hydrogen storage are incorporated in the system design. Implying a cost of €295 million that Gasunie would need to incur for the development of these storage facilities. Overall, this combination can be seen as a potent public-private partnership spearheading both the Dutch hydrogen economy and the Dutch energy transition.

Factors	**Metrics**	**Comprised of design constructs theme metrics**		
		BM-D	I-D	M-D
1. Sustainability	Level of decarbonization (acceptability)	C1; C2; T1;	A2; R2	A1
	Acceptability and support for product/service	O1; O2; O3; S1; S2; S3; F1; I1; I2; I3; I4;	R1; R3; R4; C2; C3	A2; R1; R2; R3; C4
2. Affordability	Price of energy, project & system change	F1; F2; F3	A2	R4
	Distribution of costs and benefits	C1; C2; F1; F2; F3; F4; V1; V2; V3; V4;	A1; A2; R1; R4	R2; R4; C1; C3
3. System robustness	Level of Energy security	O1; O2; P1	A2; R2; C1	A1; C2
	Resilience of the energy system (Flexibility)	T1; T2; O3; P1	A1; A2; R2; R3; C2; C3	R3; R5; C2
4. Reliability of Operations	Availability of energy	S2; S3; T1; T2; T3; O2	R1; R2; C1	A2; R3; R5; C4
	Lifetime & performance of system components	S1; O3; P1	A2; C3	R5

Table 20. Factors for the performance of the system comprised of metrics incorporated in combination 3.

5 DISCUSSION

In this chapter I will reflect on the framework, the results, limitations and implications. Foremost, I will discuss in what manner the performances of the business model change when system effects are incorporated in their design. To do this I will first compare the comprehensive business modelling framework with contemporary literature and discuss its usefulness. Then I will discuss the results and provide extra contest by discussing the combinations that were not analyzed. Followed by the limitations of this study and recommendations for future research. At the end of this chapter I will discuss the implications of my master thesis project.

5.1 RELEVANCE OF THE FRAMEWORK

In chapter one I explained that a framework which combines the business model with the system design fills a gap in scientific literature. I have not yet compared the comprehensive business model framework with literature concerning public-private partnerships. This is relevant because the comprehensive business modelling method will only work if you have parties collaborating which have authority to design the business model and the system. Most research on public-private partnerships has been completed from the perspective of the public sector (Hodge & Greve, 2018; Wall & Connolly, 2009). The comprehensive business modelling framework combines business models (i.e. the perspective of private parties) with system effects (i.e. the perspective of public parties). The framework allows to clarify the roles, responsibilities and risks within the project in a transparent manner for all stakeholders. Which is the foundation for fruitful discussions on the allocation and sharing of risks, both financially and legally. As such actors can accommodate each other during contract negotiations to ensure the presence of value in all the segments of the hydrogen value chain.

A study by Osei-Kyei & Chan (2015) on the critical success factors for public private partnerships shows that the five most important factors are: risk allocation and sharing, a strong private consortium, political support, community/public support and transparent procurement. These factors were found to be important irrespective of jurisdiction, the stage of project, sector or project model. By mapping out the business model and the system design side by side the comprehensive business model framework clarifies all prerequisites for success of the endeavor. Sharing and allocation of risk is covered by with proper designs for the factors: organization, finance, system design principles, and governance. Political support and the formation of a stronger private consortium is covered with adequate design for the factors: customer value, value exchange, and formal institutions. The incorporation of control mechanisms and adequate information exchange in the comprehensive business modelling framework improves the level of community/public support for the project. Although the factor information exchange is defined in the framework it is sadly not adequately present within this case. The same goes for transparent procurement which is mainly a result of proper information exchange internally and externally. More on this in 5.3. In another recent study by Cui, Liu, Hope & Wang (2018) four important categories were found for the implementation of PPP in infrastructure projects. [1] The first is a proper rationale for a PPP and the merit and worth of a PPP, this can be done by determining the financial package and the specific PPP application. [2] Then the decisions to undertake the PPP must be made. The decision is made based upon the PPP’s economic viability; risk management and success factors; and procurement and contract management. [3] Regulation and guidance, which is determined by the government in the manner it governs and regulates. [4] Ex-post evaluations of the PPP in which the performance is judged according to chosen criteria.

The first category is not present in the framework itself, but the merit and worth of a PPP is made clear in the introduction of this paper. Without a public-private partnership the H-vision project will simply not be developed. The framework used for this study mainly covers the second and third categories. Within the framework used in this study, the combination of business modelling and system design provides a clear view on the economic viability, success factors, and allocation of risks. Ensuring the absence of any future stakeholder agitation against the development of H-vision or the integration of hydrogen as an energy carrier. In combination with maintaining transparency and a high level of information exchange in the business model part of the framework. Public distrust and opposition will be avoided, which is reported to be the main reason for failure of some PPP projects. The comprehensive business modelling framework is a tool with which a project can be successfully integrated into an energy system to ensure smooth functioning of economic and social life in a country. As for the fourth category, while the public-private partnership for H-vision should certainly be evaluated ex-post. I argue that the ex-ante evaluation is of great value, especially when the project is heavily dependent on future political developments, macro-economic developments. Leading to the question: what level of investment is justifiable? An ex-ante evaluation is very useful to predict the outcomes of a specific development option combined with a specific system design. Providing valuable insight into the optimal combination and thus how the project should progress to avoid negative externalities or unwanted outcomes.

The above argues for the theoretical relevance of the framework. The framework still has some teething problems which effect its practical utility. To record relevant information to embody all factors requires lots of research. The application of the framework is thus time intensive. For a smaller project the application of the framework would be excessive. It only makes sense to apply the framework for large projects that effect the energy system in a significant way, i.e. effect the basic system and market principles. Apart from the application of the framework to specific projects, the framework can be abbreviated. Some factors within the framework can be left out or fused. Concerning the factors for the business model. 'Process alignment' can be left out entirely or become part of the factors 'Technology' and 'Organization'. Process alignment was the least mentioned factor by experts and is seen as a rudimentary aspect of a system integrations. Apparently, it goes without saying that technical systems and organizational processes in a project that requires collaboration of multiple actors must be aligned. The factors 'Value Exchange' and 'Information Exchange' can be fused together and called 'Value & Information exchange'. One could argue that information is a form of value. But I find it important to underline the importance of information in the framework as it is labelled as crucial in scientific literature. This new factor would in essence cover the exchange of all resources in the collaboration except for those monetary in nature. The factors: Customer value, Product/Service, Technology, Organization, and Finance are found to be crucial in developing an apt business model.

Concerning the factors for the system and market. The factors: Design perspective, Design principles, Formal institutions, and Governance are in my opinion the most important. These four factors cover the most ground necessary to design the system and market appropriately. Since the factor 'control mechanisms' was found to be important and relevant by the interviewed experts. I advise to include the factor as a theme metric in the factor 'Design principles', control mechanisms are necessary to prevent disasters that could negatively affect the integration and development of a new infrastructure project. The factor 'Organization' is virtually entirely encapsulated by the business model construct, it even is a business model factor. As such it can be left out of the system design construct in the framework.

5.2 Reflection on Results

As delineated in section 4.4 the most likely combination to be developed among the three analyzed is the medium business case with the hydrogen backbone system design. Simply because the level of investment is very acceptable for all parties. A CAPEX of 700 million by the government would practically secure cooperation from the private parties. But what are the differences between these combinations exactly, and to what extent are they caused by system effects. The performance of the minimum business model does not change, simply because there is no system design. System effects are not truly included, at the same time this is not necessary. The project is not integrated in the wider Dutch energy system but in the system of several dedicated actors in the Port of Rotterdam. Although on the micro-level, adjustments to the systems of these actors will need to be made this can and will all be done by the companies themselves. These adjustments and the design of these systems can all be covered in the technology section of classical business model methodologies. The performance of the second and third business models however improves significantly. The simplest case is that a design for the system and market opens new avenues within the business models. For instance, the inclusion of a hydrogen backbone and storage in the system design increases flexibility. Flexibility is a system effect that creates an opportunity a smaller production capacity for the ATR, resulting in a lower CAPEX which is a metric for the finance factor in the business model. In a cascading manner this cost reduction in turn creates opportunity to increase scale, with increasing scale once again comes cost reduction, an expansion of the hydrogen economy and increased customer value. Essentially making the business model more affordable and sustainable. Another example is that the design for an integrated market improves system robustness, which is paramount for the collaborating partners within the business model.

As explained in section 3.3 only three combinations were to be fully appraised in this study. However, to justify my advice on which combination should be developed I will quickly address all options. The minimal business model with the 'hydrogen backbone' would be extremely beneficial for the private parties. The government takes more risk and provides more guarantees. The H-vision partners can see this option as a project to start decarbonizing their processes while incurring small losses and generating enough revenue, in this case the NPV of the project could become positive. With the establishment of a hydrogen exchange in the Dutch market, the consumers of hydrogen in H-vision can presumably purchase hydrogen produced by third parties to further decarbonize their activities. The collaborating private parties are given an excellent position from which they can further abstain from making expensive investments to decarbonize their activities. They can essentially offload some risk to public and third parties and await technological innovations that will further reduce cost of decarbonization. For the public parties this would not be a preferred combination. There is a reduction in the amount of CO_2 emitted but the potential to reduce more CO_2 emissions is forgone in the short term.

The minimal business model combined with the 'hydrogen economy development' system design will unfold differently. Although the collaborating partners in H-vision in the short term would gain, like the 'minimal-hydrogen backbone' combination. In the long term they would certainly incur more losses due to their inaction in the short term. I believe that this system design creates an enormous demand for the use of hydrogen in the Dutch energy system. The inaction by the collaborating partners creates a large vacuum which presents an enormous opportunity for new entrants. These new entrants are not resisted in anyway and quickly grow. As a result, the collaborating partners will lose market share. So, for private parties this is a combination they should try to avoid. As for the government and other public parties this is a combination that should not be preferred but can be beneficial in the long run. There is an increased risk for economic turmoil, but the benefits are large as well. A period with an increased level of innovation in energy would ensue coinciding with the development of a more heterogenous energy system. The benefits could spill over to different sectors and even countries. Both sides stand to gain but also to lose depending on the time frame.

Medium case combined with the 'standalone' system design would not be devastating to H-visions collaborating partners. In the medium case storage of hydrogen is not crucial so this does not have to be constructed by the partners themselves. They would need to finance the project from external lenders which will demand a higher interest rate decreasing the NPV of the project further. Shareholders will not be happy, but the companies do take action to decarbonize which will help with their image. This combination is interesting for the government and other public parties since they can wait patiently for the hydrogen market to develop and take the position of 'market fixer'. However, they will not meet their goal of a 49% CO_2 emissions reduction in 2030. Which will, if we trust in scientific consensus, have disastrous consequences.

The medium business case combined with the 'Hydrogen economy development' system design would play to the advantage of the H-vision collaborating partners. The same reasons count here as for 'minimal-hydrogen backbone' combination. They can withhold expensive capital investments that is needed for increasing the production capacity of the ATR. A large part of the production of hydrogen needed to decarbonize all activities up to 2050 can be outsourced. The government and public parties will benefit as well, it is likely that the goals set in the climate agreement will be achieved. However, the government will need to take more risk which causes the distribution of rewards to be skewed in favor of the H-vision partners.

As for the maximum case with the 'standalone' system design, both public and private parties do not benefit. Although the government receives some value because it takes little risk, provides little guarantees, and in return they get a significant level of reduction in CO_2 emissions. The H-vision partners would incur heavy losses and might go bankrupt due to the energy system not being accommodating enough for the project to be integrated. This leads to some economic and national turmoil. The loss of jobs would create higher levels of unemployment and with it an exodus of knowledge to foreign countries. Citizens and expats with specific skills and tacit knowledge will look for job opportunities abroad. This is a combination that should be avoided at all costs.

The maximum case combined with the hydrogen backbone would be the ideal situation for the government and other public parties. Since private parties take an increased amount of risk and invest more than they would do under normal circumstances the government in return for moderate investments and adjustments to the system gets a reduction in CO_2 emissions of 51% in the Port of Rotterdam. Additionally, transport is facilitated by the public transmission network and for the most privately-owned distribution networks. In the long term the government will need to buy the private hydrogen pipeline networks when broad access to hydrogen is needed by citizens.

What is explained above is presented in table 19. The quick scan on the other combinations reveals a configuration of the "prisoner's dilemma" table. Which explains what was mentioned in the first chapter of this study. It sheds light as to why two completely rational sides might be reluctant to cooperate to achieve something that is in their best interests. The red cells are combinations which should be avoided at all costs. The orange cells are the combinations that are more rewarding for the government and other public parties. The green cells are the combinations where the H-vision partners and other private parties stand to gain more. The blue cells are the cells are the cells where both sides receive equal amounts of value for their investments. This thought experiment shows that for most combinations the inclusion of system effects does improve the value the private partners get from the business model. The exception is when the minimal business model is combined with the hydrogen economy development system design the additional system effects result in a decreased level of value.

Business Model \ *System Design*	**Minimal**	**Medium**	**Maximum**
Standalone	-1 \ -1	1 \ 0	-1 \ -1
Hydrogen Backbone	0 \ 1	1 \ 1	2 \ 1
Hydrogen Economy Development	0 \ 0	1 \ 2	2 \ 2

Table 21. The combinations with their according value to either actors on the public or private side.

Legenda	
Value of combination for both sides (public\private)	**1** \ **2**
Both sides prospectively incur losses	
Private partners stand to gain more value	
Public partners stand to gain more value	
Both sides prospectively receive equal value	

5.3 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This research set out to do two things. To assess the performance of the H-vision business models when system design effects are also taken into account. And to contribute to scientific literature concerning the combination of business model factors with system design factors for use in developing public-private partnerships. Both points have been achieved, albeit with moderate success. The results of this research are based upon a qualitative research using both primary and secondary data. Rigor was strived for by establishing the theoretical bases and methodology. The constructs and factors in the framework used to assess the H-vision case were identified from peer-reviewed scientific literature. As such the internal validity of this single-embedded case study is hopefully up to standards. The external validity however is low, due to the explorative and experimental nature of this research; the use within this study of one case.

A for the generalizability of the study. The heterogeneous nature of energy infrastructure projects means it is not possible to utilize the exact same framework for projects dissimilar to H-vision. Entailing projects that are not related to the production or use of hydrogen as an energy carrier. The method of comprehensive business modelling on the other hand is interesting and can be applied to all infrastructural projects developed by a public-private partnership. As for the completeness of the framework. I am confident that the factors utilized in this research are valid and functional. Some experts indicated that they used the Business Model CANVAS, and in the H-vision project a variation of the Business Model CANVAS was applied as well. For the assessment of risks for the business model the "TECOPS" framework is often used. Categories in the TECOPS model is: Technical, Economical, Commercial, Organizational, Political, and Societal. For the business model, two factors stood out for repeatedly being ignored: information exchange and process alignment. Process alignment was often found to be self-evident in its importance thus experts refrained from mentioning this factor. Information exchange was deemed important when pointed out to experts. But to my surprise this factor was not mentioned by experts unaided. It is my opinion that the proper diffusion of knowledge and information is crucial for a business model, especially when a collaboration is developing the business model. The old saying *"communication is key"* springs to mind. Scientific literature confirms that the performance and innovativeness of a firm, collaboration or partnership increases with the application of a form of knowledge management (Cui et al., 2018; Darroch, 2005; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007b; McNamara, 2015). A method for open and frequent communication of information between internally and externally promotes understanding among all stakeholders. As a result information asymmetries are reduced, which is beneficial for effective collaboration (Blok, 2018). As for the infrastructural and market factors there were none that were repeatedly not mentioned.

I am much less confident concerning the inclusion of certain metrics in the framework. The current metrics could be more extensively tested against expert scrutiny. Moreover, I am convinced that more applicable metrics can be found to indicate whether a factor is present. This can be done by interviewing experts in the field of energy; performing a more detailed survey of scientific literature; and performing a survey of contemporary business models applied by corporations to identify relevant factors. A factor is then found to be relevant if it was found in literature or mentioned by an expert. Future research might examine more cases by using the comprehensive business modelling method so that the completeness and relevance of the framework can be further explored. Such a cross-case analysis will allow the more precise assessment of the organizational, technical and institutional similarities and differences. Further defining the framework and exploring implications for business, policy and governance. This would greatly improve the replicability of the framework.

Apart from the framework itself, this research could have been improved by applying it as intended by making nine combinations as delineated in section 3.5. In the previous section I have briefly addressed the other combinations to produce a more refined advice on which combination should be developed. This would have provided a larger frame of reference that could have been used to refine recommendations for the development of H-vision. Especially interesting are the following three combinations: 'minimum-hydrogen economy development', 'medium-hydrogen economy development', and the 'maximum-hydrogen backbone'. These three combinations have not been analyzed in this study, but the quick scan indicates the promise of value for both public and private parties. These combinations could be subject to further research and the application of the comprehensive business modelling framework to substantiate

A somewhat larger limitation of this research is the (partial) omittance of the complex interdependencies between the gas (heat), electricity and transport sectors. The reason to leave out these interdependencies was quite simply that the scope would become too large, effecting the conciseness of this study. However, I must state that the interdependency between the gas and electricity infrastructure is of great importance. These interdependencies will naturally have implications at an organizational, technical and institutional level, especially for integrating green hydrogen projects into the energy system. I am positive that, if necessary, with the comprehensive business modelling method an analyst can address all sectors. Because this research witnessed a limitation in resources, especially time. It was regrettably not possible to overcome these limitations. Contemplating about this graduation project I have come to realize that I would have liked to do some things differently. Alas I think this conceptual process is natural within scientific work.

5.4 IMPLICATIONS

Even with the limitations of this study I am confident that the method and framework for comprehensive business modelling is relevant as explained in section 5.1. I do want to stress that using the framework is heuristic. The factors are generalizable, but the metrics are not and have to be examined and clearly understood in context. The framework is merely a tool for managers to gain more insight when integrating and developing sustainable energy projects that have a disruptive effect on the energy system. Especially for managers from different organizations that need to collaborate it provides the opportunity to reduce uncertainty attached to the decision for allocating valuable resources by creating a comprehensive view of the relations between the project, the system and the market.

The question arises to what extent the method of comprehensive business modelling is different from current scenario analyses used for such projects. Scenarios are coherent and plausible stories, told in words and numbers, about possible co-evolutionary pathways of combined human and environmental/technical systems (Swart, Raskin, & Robinson, 2004). Analyzing these scenarios allows to systematically frame uncertain possibilities for strategic decision making. The comprehensive business modelling method shows quite some similarities to scenario analysis. It helps to specify future possible conditions, the identification of long-term risks, and a bandwidth of available actions necessary to realize predetermined goals.

However, where the comprehensive business modelling method stands apart is that it does not incorporate the dynamics of change. The framework simply provides static designs for the business model and the system. Scenario analysis is concerns painting a coherent and engaging picture about the future and determine what actions need to be made to prevent or achieve such a future. The comprehensive business model concerns the making of a blueprint emphasizing the technical feasibility and implications of distinct design options, rather than to explore how such futures might unfold. As I mentioned in section 2.3, I do recognize that there is a dynamic facet to the integration of technologies in a system. Which is can provide context on the further implications of the integration of hydrogen in the Dutch energy system.

The H-vision project can be seen as a niche, which is a controlled environment in which experiments are made with new technologies (Smith & Raven, 2012). New technological innovations emerge and mature within niches to eventually become the dominant design within a technological innovation system. Currently fossil fuels are the dominant energy carriers within the socio-technical regime. Momentarily the exogenous environment or “landscape”, i.e. macroeconomics, cultural attitudes and macro-politics, is exerting pressure on the socio-technical regime to change. The urgency of climate change is requiring the current Dutch energy system to adapt. As such it is creating a window of opportunity for the integrations of niches out of which new sustainable technological innovations can arise. All stakeholders in the H-vision project must understand that this window of opportunity will not remain open for very long. The time to act is now. A sharp-cut vision must be developed and governed with consistent policy by the public sector, the private sector must be willing to take more risk, and they must both work together to successfully transition to a sustainable energy system. My hope is that this research addresses and conceptualizes how to manage such a transition across interconnected systems, in a way that addresses social and economic sustainability as well as reducing environmental impacts.

My advice is that the Dutch government and the H-vision partners must jointly work towards a design that is very similar to either the medium business model combined with the hydrogen backbone or the maximum business model combined with the hydrogen economy development. These two combinations can deliver the most value overall. The primary difference between the two concerns the values for sustainability and affordability. The medium-backbone combination is more affordable but less sustainable, the maximum-hydrogen economy development combination is less affordable but more sustainable. If the Dutch government wants to keep the Dutch energy transition affordable, as it has stated is its intention. Then the Dutch government should develop the hydrogen backbone system design and accommodate the development of at least the medium business case. As for the private partners my advice is to develop the medium business model. Less value can be begotten with the minimal option. More value can potentially be begotten with the maximum option, but it is accompanied with more risk. Major losses will be incurred if the government does not provide a basic hydrogen infrastructure.

My opinion however is that the public-private partnership should develop the maximum business model and the hydrogen economy development system design. Quite simply because I am an optimist and am confident that this is the in the best interest of the Netherlands. It has a high level of sustainability, high level of system robustness and a high level for the reliability of operations. The only negative aspect is affordability. Implying that the Netherlands will experience some minor economic turmoil and companies in the short term will generate less profit. But this is a necessary evil that must be tolerated in order to overcome the challenge that is the energy transition. Recently, I have been watching a documentary about the early days of space exploration with the result of getting man to the moon. Although I had heard the speech made by John F. Kennedy in 1962 before, it especially struck me now.

"*We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win, and the others, too.".*

If the urgency of climate change, advocated by a large majority of the scientific community, is to be accepted. Then the energy transition is one such challenge that we should be unwilling to postpone and want to win. If we achieve this goal it will indeed serve to organize and measure the best of our 'energies', skills and willpower.

6 Conclusion

In this study I assessed the need and relevance for a framework that could improve the performance of a business model for the production of blue hydrogen. The business model approach and the socio-technical system approach have both been applied for the development of the framework. So far there has not been any attempt to combines these approaches, but they show some overlap and promising complementarities. In this thesis project I have studied state of the art literature in both the business model and socio-technical system fields. This led to the conceptualization of the comprehensive business modelling framework. In this framework eight factors were used to assess the business model: ‘customer value’, ‘product/service’, ‘technology’, ‘organization’, ‘finance’, ‘value exchange’, ‘information exchange’, and ‘process alignment’. Six factors were used to assess the system design. Three to examine the technical infrastructure of the Dutch energy system: ‘design perspective’, ‘design principles’, and ‘control mechanisms’. The other three were used to examine the energy market: ‘formal institutions’, ‘governance’, and ‘organization’. The degree to which these factors were designed affected the outcome of the system integration. The factors to test the outcome of the system integration were: ‘sustainability’, ‘affordability’, ‘reliability’, ‘robustness’. These factors were tested against expert scrutiny to establish their relevance for integrating a hydrogen related project into the energy system. By using the comprehensive business modelling framework three combinations of a specific business model and system design were intensively assessed to see what the implications of these combinations were for the integration of H-vision into the Dutch energy system. The other six combinations were discussed in section 5.3. The results helped in answering the following research question:

How does the performance of the H-vision business model change when system effects are incorporated in the design?

The conclusion is that the performance of the business model from the perspective of a public-private partnership improves when system effects are incorporated in its design. In almost all combinations the inclusion of system effects resulted in an increased level of value for both the private and public partners. To a certain extent this is logical and perhaps unsurprising. If you fine tune an object with an environment, the object integrates better or successfully into that environment. The comprehensive business modelling method is presented as a qualitative analysis tool for managers to use when partaking in a public-private partnership for the development of an energy infrastructure project. The use of this tool can offer a series of benefits. In general, it provides an overview of all aspects that are necessary to address when developing such a project. Stimulating transparency and tying together the roles and responsibilities of all partners within the collaboration. Improving the distribution of risks and rewards accompanied by a reduction of inefficiencies and negative externalities. The framework however is very time intensive in its application and its use is only worthwhile when assessing large projects that effect the energy system in a significant manner. My advice is that the private partners in H-vision should collaborate with the government in the form of a PPP to develop the medium business model for H-vision with a system design similar to that of the hydrogen backbone. Based on this foundation new projects can be established to achieve a smooth and cost-effective energy transition.

I hope that this study has successfully laid out potential research avenues and presented the comprehensive business modelling framework as a promising analytical tool for improving the management of integrating innovations in the energy system.

7 REFERENCES

Air Products. (2018). Air Products Holds Ribbon - Cutting for World - Class SMR at Covestro in Texas. Retrieved from http://www.airproducts.com/Company/news-center/2018/06/0620-air-products-holds-ribbon-cutting-for-world-class-smr-at-covestro-in-texas.aspx

Amirante, R., Cassone, E., Distaso, E., & Tamburrano, P. (2017). Overview on recent developments in energy storage: Mechanical, electrochemical and hydrogen technologies. *Energy Conversion and Management*, *132*, 372–387. https://doi.org/10.1016/J.ENCONMAN.2016.11.046

Barreto, L., Makihira, A., & Riahi, K. (2003). The hydrogen economy in the 21st century: a sustainable development scenario. *International Journal of Hydrogen Energy*, *28*(3), 267–284. https://doi.org/10.1016/S0360-3199(02)00074-5

Baxter, G., & Sommerville, I. (2011). Socio-technical systems: From design methods to systems engineering. *Interacting with Computers*, *23*(1), 4–17. https://doi.org/10.1016/j.intcom.2010.07.003

Blok, V. (2018). Information asymmetries and the paradox of sustainable business models: Towards an integrated theory of sustainable entrepreneurship. In *Sustainable Business Models* (pp. 203–225). Springer.

Boulding, K. E. (1956). General Systems Theory-The Skeleton of Science. *Management Science*, *2*(3), 197–208. https://doi.org/10.1287/mnsc.2.3.197

Bouwman, H., De Vos, H., & Haaker, T. (2008). *Mobile service innovation and business models*. *Mobile Service Innovation and Business Models*. https://doi.org/10.1007/978-3-540-79238-3

Breij, B. (2018). Groningen relatief één na meest vervuilende provincie, uitstoot flink toegenomen (update). *Dagblad Van Het Noorden*, pp. 1–4.

Bryman, A. (2012). *Social research methods Bryman*. *OXFORD University Press*. https://doi.org/10.1017/CBO9781107415324.004

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

CBS. (2017). Aardgasexport in drie jaar gehalveerd. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2017/09/aardgasexport-in-drie-jaar-gehalveerd

CBS. (2018). CO2-uitstoot in 2017 gelijk aan die in 1990. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2018/37/co2-uitstoot-in-2017-gelijk-aan-die-in-1990

CE Delft. (2018). *Feasibility study into blue hydrogen Feasibility study into blue hydrogen*.

Chesbrough, H., & Rosenbloom, R. S. (2002). The role of the business model in capturing value from innovation. *Industrial and Corporate Change*, *11*(3), 529–555. https://doi.org/10.1093/icc/11.3.529

Chesbrough, Henry. (2007). Business model innovation: it's not just about technology anymore. *Strategy & Leadership*, *35*(6), 12–17. https://doi.org/10.1108/10878570710833714

Coalitie, W. (2018). *Waterstof Coalitie – Vier pijlers onder een duurzame waterstofeconomie in Waarom waterstof*.

Cui, C., Liu, Y., Hope, A., & Wang, J. (2018). Review of studies on the public–private partnerships (PPP) for infrastructure projects. *International Journal of Project Management*, *36*(5), 773–794. https://doi.org/10.1016/j.ijproman.2018.03.004

Darroch, J. (2005). Knowledge management, innovation and firm performance. *Journal of Knowledge Management*, *9*(3), 101–115. https://doi.org/10.1108/13673270510602809

De Waterstof Coalitie. (2018). *WATERSTOF ESSENTIËLE BOUWSTEEN ENERGIETRANSITIE MANIFEST WATERSTOF COALITIE*. Retrieved from https://www.vno-ncw.nl/sites/default/files/manifest_waterstof_coalitie.pdf

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

Elam, C. C., Padró, C. E. G., Sandrock, G., Luzzi, A., Lindblad, P., & Hagen, E. F. (2003). Realizing the hydrogen future: the International Energy Agency's efforts to advance hydrogen energy technologies. *International Journal of Hydrogen Energy*, *28*(6), 601–607. https://doi.org/10.1016/S0360-3199(02)00147-7

Emery, F. E. (1959). Characteristics of socio-technical systems: A critical review of theories and facts about the effects of technological change on the internal structure of work organisations; with special reference to the effects of higher mechanisation and automation. *Tavistock Institute of Human Relations.*

Energieonderzoek Centrum Nederland. (2017). *Nationale Energieverkenning 2017*.

European Commission. (2018). *A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. Retrieved from https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf

Foss, N. J., & Saebi, T. (2016). Fifteen Years of Research on Business Model Innovation: How Far Have We Come, and Where Should We Go? *Journal of Management*, *43*(1), 200–227. https://doi.org/10.1177/0149206316675927

Gasunie. (2018). *Verkenning 2050 Verkenning*.

GasUnie. (2018). *GasUnie Transport Services: Annual Report* (Vol. 1).

Gasunie Transport Services. (2017). *Netwerk Ontwikkelingsplan 2017*.

Geels, F. W. (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

Gustafsson, J. (2017). Single case studies vs. multiple case studies: A comparative study. *Academy of Business, Engineering and Science Halmstad University, Sweden*, 1–15. https://doi.org/January 12, 2017

H-Vision. (2019). *Blue hydrogen as accelerator and pioneer for energy transition in the industry*.

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

Hedman, J., & Kalling, T. (2003). The business model concept: Theoretical underpinnings and empirical illustrations. *European Journal of Information Systems*, *12*(1), 49–59.

https://doi.org/10.1057/palgrave.ejis.3000446

Heikkilä, M., Bouwman, H., Heikkilä, J., Solaimani, S., & Janssen, W. (2016). Business model metrics: an open repository. *Information Systems and E-Business Management*, *14*(2), 337–366. https://doi.org/10.1007/s10257-015-0286-3

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007a). 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

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007b). 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

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

Hodge, G., & Greve, C. (2018). Contemporary public–private partnership: Towards a global research agenda. *Financial Accountability and Management*, *34*(1), 3–16. https://doi.org/10.1111/faam.12132

International Energy Agency. (2014). *Energy Policies of IEA Countries: Netherlands 2014*. https://doi.org/https://doi.org/10.1787/9789264210462-en

Kimkes, S., & van ’t Wiel, R. (2019). Bouw aan de Nieuwe Water(stof)weg. Retrieved from https://www.shell.nl/media/venster/building-on-the-new-water.html?cid=Social:LINKEDIN_COMPANY:Default_Netherlands_2019:2299399442:LINKEDIN:shell&linkId=67155802

Klijn, E., & Teisman, G. R. (2002). Institutional and Strategic Barriers to Public-Private Partnership: An Analysis of Dutch Cases, (September), 9–11.

Künneke, R., & Fens, T. (2007). Ownership unbundling in electricity distribution : The case of The Netherlands. *Energy Policy*, *35*, 1–10. https://doi.org/10.1016/j.enpol.2006.05.008

Kurtz, J., Peters, M., Muratori, M., & Gearhart, C. (2018). Renewable Hydrogen-Economically Viable: Integration into the U.S. Transportation Sector. *IEEE Electrification Magazine*, *6*(1), 8–18. https://doi.org/10.1109/MELE.2017.2784631

Marbán, G., & Valdés-Solís, T. (2007). Towards the hydrogen economy? *International Journal of Hydrogen Energy*, *32*(12), 1625–1637. https://doi.org/10.1016/J.IJHYDENE.2006.12.017

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

Mazzucato, M. (2011). *The Entrepreneurial State*. *Choice Reviews Online* (Vol. 51). https://doi.org/10.5860/CHOICE.51-2973

McDonald, O. (2019). Eisen kabinet aan subsidie voor CO2-opslag vallen mee. *Energia*, pp. 1–2.

McDowall, W., & Eames, M. (2006). Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. *Energy Policy*, *34*(11), 1236–1250. https://doi.org/10.1016/J.ENPOL.2005.12.006

McDowall, W., & Eames, M. (2007). Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures. *International Journal of Hydrogen Energy*, *32*(18), 4611–4626. https://doi.org/10.1016/J.IJHYDENE.2007.06.020

McNamara, M. W. (2015). Unraveling the characteristics of mandated collaboration. *Advancing Collaboration Theory: Models, Typologies, and Evidence*, 65–86. https://doi.org/10.4324/9781315749242

Melieste, R. (2017). DEEP DECARBONIZATION IN THE PORT OF ROTTERDAM Port of Rotterdam, (november).

Ministerie van Economische Zaken. (2016). *Energieagenda*. https://doi.org/97015

Ministerie van Economische Zaken en Klimaat. Kamerbrief: Verbreding van de SDE+ naar de SDE++ (2019).

Minsterie van waterstaat en infrastuctuur. (2019). *Inspectie Leefomgeving en Transport (ILT) Meerjarenplan 2019-2023*. Retrieved from http://www.ilent.nl/

Mitchell, D., & Coles, C. (2003). The ultimate competitive advantage of continuing business model innovation. *Journal of Business Strategy*, *24*(5), 15–21. https://doi.org/10.1108/02756660310504924

Moreno-Benito, M., Agnolucci, P., & Papageorgiou, L. G. (2017). Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development. *Computers and Chemical Engineering*, *102*, 110–127. https://doi.org/10.1016/j.compchemeng.2016.08.005

Nastasi, B., & Lo Basso, G. (2016). Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. https://doi.org/10.1016/j.energy.2016.03.097

Navigant. (2019). Verkenning uitbreiding SDE + met industriële opties.

Nijpels, E. (2018). *Ontwerp van het Klimaatakkoord*. Retrieved from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2018/12/21/ontwerp-klimaatakkoord/Ontwerp+van+het+Klimaatakkoord.pdf

Ortt, J. R., & Duin, P. A. Van Der. (2008). The evolution of innovation management towards contextual innovation, (May 2014). https://doi.org/10.1108/14601060810911147

Ortt, J. R., Langley, D. J., & Pals, N. (2013). Ten Niche Strategies To Commercialize New High-Tech Products, (June).

Osei-Kyei, R., & Chan, A. P. C. (2015). Review of studies on the critical success factors for public-private partnership (PPP) projects from 1990 to 2013. *International Journal of Project Management*, *33*(6), 1335–1346. https://doi.org/10.1016/j.ijproman.2015.02.008

Osterwalder, A., & Pigneur, Y. (2005). Clarifying Business Models : Origins , Present , and Future of the Concept Clarifying Business Models : Origins , Present , and Future of the Concept. *Business Horizons*, *16*(1), 1–25. https://doi.org/10.1.1.83.7452

Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: a handbook for visionaries, game changers, and challengers*. https://doi.org/10.1523/JNEUROSCI.0307-10.2010

PBL. (2019a). *Economische effecten van CO2-beprijzing: varianten vergeleken*.

PBL. (2019b). *Effecten ontwerp klimaatakkoord*.

Plomp, A. ., Barry, C., Kroon, P., McAlpine, I., & Mozaffarian, M. (2015). *Emissies van raffinaderijen, vanuit concurrentieperspectief*.

Porter, M. (1990). Competitive Advantage of Nations. *Competitive Intelligence Review*. https://doi.org/10.1002/cir.3880010112

Preuster, P., Alekseev, A., & Wasserscheid, P. (2017). Hydrogen Storage Technologies for Future Energy Systems. *Annual Review of Chemical and Biomolecular Engineering*, *8*(1), 445–471. https://doi.org/10.1146/annurev-chembioeng-060816-101334

Righi, A. W., & Saurin, T. A. (2015). Complex socio-technical systems: Characterization and management guidelines. *Applied Ergonomics*, *50*, 19–30. https://doi.org/10.1016/j.apergo.2015.02.003

Rijksoverheid. (2017). *Vertrouwen in de toekomst? Regeerakkoord 2017-2021* (Vol. 79). https://doi.org/10.1007/s41196-017-0532-y

Rijksoverheid. (2018). *CLO: Aanbod en verbruik van energiedragers in Nederland , 2016*.

Rijksoverheid. (2019a). Klimaatakkoord, 239. Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2019/06/28/klimaatakkoord

Rijksoverheid. (2019b). Wetsvoorstel minimumprijs CO2 bij elektriciteitsopwekking ingediend. Retrieved from https://www.rijksoverheid.nl/actueel/nieuws/2019/06/04/wetsvoorstel-minimumprijs-co2-bij-elektriciteitsopwekking-ingediend

Römgens, B., & Dams, M. (2018). *VNPI CO 2 Reductie Roadmap van de Nederlandse raffinaderijen*.

Scholten, D. (2019). *The Geopolitics of Renewables*.

Scholten, D., & Künneke, R. (2016). Towards the comprehensive design of energy infrastructures. *Sustainability (Switzerland)*, *8*(12). https://doi.org/10.3390/su8121291

Schot, J., & Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management*, *20*(5), 537–554. https://doi.org/10.1080/09537320802292651

Schwartz, K. (2019). ' Als er een CO2-heffing komt , is het klaar met Tata Steel ,' pp. 1–5. Retrieved from https://www.trouw.nl/home/-als-er-een-co2-heffing-komt-is-het-klaar-met-tata-steel-~ad5efecf/

Shafer, S. M., Smith, H. J., & Linder, J. C. (2005). The power of business models. *Business Horizons*, *48*(3), 199–207. https://doi.org/10.1016/j.bushor.2004.10.014

Sharma, S., & Ghoshal, S. K. (2015). Hydrogen the future transportation fuel: From production to applications. *Renewable and Sustainable Energy Reviews*, *43*, 1151–1158. https://doi.org/10.1016/J.RSER.2014.11.093

Simbolotti, G. (2010). CO 2 Capture and Storage (CCS). *IEA Energy Technology Network*, (October), 2013.

Staatstoezicht op de Mijnen. (2019). Jaarplan 2019: Veiligheid essentieel voor slagen energietransitie. Retrieved from https://www.sodm.nl/actueel/nieuws/2019/03/05/jaarplan-2019

Swart, R. J., Raskin, P., & Robinson, J. (2004). The problem of the future: Sustainability science and scenario analysis. *Global Environmental Change*, *14*(2), 137–146.

https://doi.org/10.1016/j.gloenvcha.2003.10.002

Teece, D. J. (2010). Business models, business strategy and innovation. *Long Range Planning*, *43*(2–3), 172–194. https://doi.org/10.1016/j.lrp.2009.07.003

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

Trist, E. (1981). The Evolution of socio-technical systems: a conceptual framework and action research program.

Utterback, J. (1994). Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change. *University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship*.

van den Noort, A., Sloterdijk, W., Vos, M., & Lieffering, J. (2017). *DNV GL Verkenning waterstofinfrastructuur*.

van Santen, H., Rijlaarsdam, B., & van der Walle, E. (2019). Kolencentrales kunnen wel eens de oplossing zijn - NRC. *NRC*, pp. 1–7. Retrieved from https://www.nrc.nl/nieuws/2019/01/25/kolencentrales-kunnen-wel-eens-de-oplossing-zijn-a3651813

van Wijk, A., Rhee, G. van, Reijerkerk, J., Hellinga, C., & Lucas, H. (2019). *Naar een groene waterstofeconomie in Zuid-Holland Een visie voor 2030*.

Vogel, R., Luiijf, E., Maas, N., Dijkema, G., & Zielstra, A. (2014). *Klimaatadaptie en energie-infrastructuur*.

Wall, A., & Connolly, C. (2009). The private finance initiative: An evolving research agenda? *Public Management Review*, *11*(5), 707–724. https://doi.org/10.1080/14719030902798172

Wijk, A. Van, & Hellinga, C. (2018). *Waterstof, de sleutel voor de energietransitie*. Retrieved from http://edepot.wur.nl/333952

Zott, C., Amit, R., & Massa, L. (2011). The Business Model: Recent Developments and Future Research. *Journal of Management*, *37*(4), 1019–1042. https://doi.org/10.1177/0149206311406265

8 APPENDIX

8.1 APPENDIX 1 – BUSINESS MODEL METRICS REPOSITORY

Perspectives	Theme metrics
Customer value *Value uniqueness* *Quality*	C1. Created customer value (qualitative description): unique; new to the world; user experience; perceived customer benefit; brand image; # of referrals; attraction of media; price, product range and flexibility of product; regulation-related and non-tangible values C2. Market segment and market share: e.g., reach and depth of customer relations; new and repeat business; customer costs; # of countries/areas; search costs, communication; sales growth; sales volume; customer profitability; average revenue per customer (ARPU); customer lifetime value; profit/revenue per customer segment/per product; customer loyalty; average order size; opportunity size C3. Website-related indicators: e.g., # of hits; page views; click-throughs; # of unique visitors; # of repeat visitors; % of online sales abandoned before completion; % of customers who have personalized their interfaces; duration of stay (stickiness); registered users; conversion rate; cross-sell ratio; channel mix change (Bouwman 2003; Dubosson-Torbay et al. 2002; Ferreira et al. 2012; Heikkilä et al. 2014; Johnson et al. 2008; Rayport and Jaworski 2001)
Service *Service-related*	S1. Service Development life cycles: development time of new service (concepts); time to first proposal; # of customer-requested features added per upgrade S2. Quality: e.g., conformance to specifications; product/service performance; availability; reliability; transparency; product/service defect/failure rates; quality delivery; time between order and receipt (delivery time service); average time to respond to customer request; out-of-stock positions; on-time shipments; shipment accuracy; % of orders delivered to correct address; packaging quality S3. Satisfaction: e.g., service level; SERVQUAL or SERVPERF; satisfaction barometer; # of customer complaints; level of billing errors; cycle time to respond to customer complaints S4. Sustainability: viability; loyalty; level of customer churn; customer retention (Dubosson-Torbay et al. 2002; Eckerson 2009; Edvinsson and Malone 1997; Ghalayini et al. 1997; Heikkilä et al. 2014; Johnson 2010; Johnson et al. 2008; Kaplan and Norton 1992, 1993, 1996; Keegan et al. 1989; Neely et al. 2002; Smith 2006; Tseng et al. 2009; Venkatraman and Ramanujam 1986)
Technology *Applications* *Architecture* *Hardware* *Data* *Infrastructure*	T1. Architectural complexity: # of applications; architecture-related indicators; platform-related indicators; cloud-related metrics; time for software and hardware implementation; extensibility T2. Data complexity: e.g., consolidation of databases; # of decentralized (customer) databases; data integration; data availability T3. Interoperability: metrics of interoperability of systems: % cross-system collaboration; system and information quality metrics T4. Accessibility and Up-time: 24-7 availability and downtime; response time; average time to load a page; # of languages; help desk calls; disaster recovery; mean time between failures; data security/integrity (Dubosson-Torbay et al. 2002; Edvinsson and Malone 1997; Ghalayini et al. 1997; Heikkilä et al. 2014; Rayport and Jaworski 2001)

Perspectives	Theme metrics
Organization (internal and external) *Organization network (internal, external)* *Complexity density structure*	O1. Number of internal partners: # of units and departments; # of organizational layers involved; # of (skilled) employees; roles and responsibilities O2. Access to resources: access to business network; suppliers, external and internal resources; inventory levels; capacity and expertise; flexibility; quality O3. Number of external partners: # of Tier-1 (core network partners), Tier-2 (replaceable provider and product/service) and Tier-3 (partners included based on market availability) network partners; % cross unit/organizational collaboration O4. Characteristics of (internal) Network: size; inclusiveness; connectivity; density; centralization; symmetry; brand; owned versus outsourced manufacturing (Bouwman 2003; Dubosson-Torbay et al. 2002; Eckerson 2009; Edvinsson and Malone 1997; Heikkilä et al. 2014; Johnson et al. 2008; Ferreira et al. 2012; Graser et al. 2005; Smith 2006)
Finance *Profitability* *Revenues* *Cost* *Risk*	F1. Network value: value created by core service for core provider as well as for the ecosystem; profit-related metrics F2. Profitability: ROI; NPV; EPS; EBIT(A); net profit; profit margin; unit margin; unit pricing; turnover; revenue (growth) (mix); return on equity; cash flow; market capitalization; share price; forecast reliability; sales backlog; project profitability; time to break even F3. Costs: total expenses; CAPEX; OPEX; development costs; investments in technology; marketing costs; operational costs/loss; cost efficiency; fixed cost investment; cost control F4. Risk: risk indicators; credit items; credit terms (Dubosson-Torbay et al. 2002; Eckerson 2009; Edvinsson and Malone 1997; Heikkilä et al. 2014; Johnson et al. 2008; Kaplan and Norton 1992, 1993, 1996; Smith 2006; Tseng et al. 2009; Venkatraman and Ramanujam 1986)
Value exchange *Value exchange in organization network*	V1. Number of partners: # involved in value exchange (transactions); # of new (innovative) projects started; centrality of specific actors in value exchange V2. Value exchange between partners: value exchange (contracts) between upstream and downstream suppliers and customers; share of business V3. Value attributed to: transactions, goods, resources and capabilities shared and exchanged within and between organization(s) V4. Value conflicts: dependencies; cost sharing; risk sharing; trust between network partners; commitment of partners (Ferreira et al. 2012; Heikkilä et al. 2014; Venkatraman and Ramanujam 1986)

Perspectives	Theme metrics
Information exchange *Information/data/knowledge availability* *Exchange and flow in organization network* *Information system quality*	I1. Number of partners: # involved in data, information and knowledge exchange; strategic information availability ratio I2. Data exchange: data, information and knowledge exchange among core partners (as percentage of total information exchanged); flow between upstream and downstream suppliers and customers; information quality; data volumes; information errors or conflicting information I3. Information accessibility: # of access points to external information systems; # of shared information systems; # of dedicated contact persons on partner's side; shared customer profiles I4. Knowledge development: suppliers' development; collaboration (Kaplan and Norton 1992, 1993, 1996; Ferreira et al. 2012; Heikkilä et al. 2014)
Process alignment, internal and external *Process intensity* *Process quality (efficiency, effectiveness)* *Diversity of processes* *Process flow*	P1. Number of primary processes: (less redundancy); # of mono/bi/multi-directional processes; length of relationship; # of (alternative) suppliers; goods, resources and capabilities shared and exchanged among organizations P2. Process throughput: average duration; utilization rate; average response time; average handling time for completed "cases"; performance according to SLA (bugs, complaints); forecast stability; JIT; time to market; delayed deliveries (of components) P3. Process variety: process standardization; # of process conflicts; process complexities; dependencies; commonality (Edvinsson and Malone 1997; Heikkilä et al. 2014; Johnson et al. 2008; Neely et al. 2002; Tseng et al. 2009)

Retrieved from Heikkillä et al. (2016)

8.2 APPENDIX 2 – INTERVIEWS

SUMMARY

The experts all agreed that hydrogen as an energy carrier will become an important part of the Dutch energy system. The general consensus is that it will mainly be used in industry, transport and the built environment. All are of opinion that blue hydrogen is crucial for curbing CO2 emissions in the short term and green hydrogen will be important to curb CO2 emissions in the long term. The interdependency of the gas and electricity network is underscored by all experts. All the factors were mentioned by at least one expert. The two factors that were consistently not mentioned were information exchange and process alignment. When the experts were made aware of this, they were all of opinion that information exchange was of importance. Process alignment was not necessarily found crucial for business models, and others found itself explanatory that the alignment of process in a collaboration should be executed. In the tables below the factors are delineated against the experts. A (x) indicates that the expert mentioned the factor to some degree themselves. A (o) indicates that the expert found the factors relevant after he/she was made aware that he/she did not mention the factor. If nothing was marked the expert did not find the factor relevant or crucial for the integration of a project. The interviews were used to test if the factors were relevant for the comprehensive business modelling of a public-private partnership hydrogen infrastructure project.

Business model

Factors	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Customer Value	o	x	x	x	o	x	x
Product/Service	x		x	x	o	x	x
Technology	o	x	x	x	x	x	x
Organization	x	x	o	x		x	x
Finance	x	x	x	x	x	x	x
Value Exchange	x		o	x	x	x	x
Information Exchange	o	x	o	o	x	o	o
Process Alignment			o	x	o	o	o

System and Market design

Factors	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Design perspective	x	x	x	x	x	x	x
Design principles	x	x		x	x	x	x
Control mechanisms	o	x	x	x	x	o	
Formal Institutions	o	x	x		x	x	o
Governance	x	x	x	x	o	x	x
Organization	x	o	o	x		o	x

8.2.1 Interview: [redacted] 18-06-2019

Punt 1. Visie waterstof als energiedrager in Nederland van interviewde

<u>Open vraag:</u> *Wat is uw visie voor waterstof als energiedrager in Nederland.*

Waterstof is potentieel één van de meest veelzijdige opties voor een duurzaam energiesysteem die we momenteel hebben. Omdat het toestaat dat energie opgeslagen kan worden in gasvorm, waterstof kan warmte leveren en het kan elektriciteit leveren. Langzamerhand begint in Nederland het besef te komen dat niet alles met elektronen af kunnen. Het is gewoon niet mogelijk om de gehele Noordzee vol te zetten met windmolens. Met name dat er in de industrie behoefte is aan moleculen, voor de petrochemie en de staalindustrie is waterstof een goede optie om CO2 neutraal te produceren. De grootste klappen betreft CO2-reductie zullen zeker op de korte termijn 5-10 jaar gemaakt worden door blauwe waterstof te gebruiken in de industrie en op de langere termijn groene waterstof.

<u>Open vraag:</u> *Wat verandert er als waterstof geïntegreerd wordt in het Nederlandse energiesysteem?*

Infrastructuur systeem hebben en een marktstructuur moet aanwezig zijn. Infrastructuur zorgt ervoor dat ervoor zorgt dat het waterstof van de producent naar de klant komt. Marktstructuur zorgt ervoor dat de klant kan kopen wat hij nodig heeft. Deze structuren moeten aanwezig zijn indien je snel schaal wilt creëren, van grijze waterstof, snel naar blauw en dan door naar groen. Schaal wil je hebben om de kostprijs omlaag te brengen. Op het gebied van marktstructuur zijn we hier dus mee bezig in de vorm van certificaten van oorsprong dit project heet dus CertifHy. Gelukkig zijn GasUnie en Tennet nu gezamelijk bezig om de oplossing te vinden om hun infrastructuur aan te passen. Deze optimalisatie qua kosten en tijd – een nieuwe hoogspanningsleiding kost tegenwoordig tot 15 jaar om te bouwen – door integratie van hun beider systemen

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

<u>Open vraag:</u> *Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland?*

Wij zijn een platform, we hebben geen eigen middelen om projecten op te zetten. Wij brengen de belangrijkste spelers bij elkaar. Dit doen we momenteel erg veel binnen de mobiliteit. We hebben wel meegeholpen met het opstellen van het klimaatakkoord en de doelstellingen daarin. De inspanningsverplichting was 50 tankstations in 2025. We zijn nu druk bezig met de implementatie van de RED 2 naar NL wetgeving – we zoeken naar opties om de groene H2 een push te geven door beloningssystemen.

<u>Open vraag:</u> *Welke elementen worden er gebruikt om de businessmodellen voor deze projecten te ontwerpen/toetsen?*

Ik heb geen weet van de specifieke factoren die worden gebruikt omdat we niet betrokken zijn bij de beslissingen om te investeren.

<u>Open vraag:</u> *Welke factoren vindt u dat er gebruikt moeten worden om de businessmodellen van dit soort projecten te toetsen.*

- De risico's van dit soort projecten moeten voor de verschillende partners verschillend gewaardeerd worden. De acceptabele returns moeten voor alle partijen beter gedefinieerd worden. Een gemeente heeft natuurlijk andere eisen aan returns dan dat van een bank of bedrijf. Een voorbeeld is dat ING het warmtenet in de regio Zuid-Holland bereid was te financieren maar pas als het opereert. Ze hadden geen zin om het constructie risico op zicht te nemen.
  Je zou dus ook de businessmodellen moeten innoveren om waterstof projecten te ontwikkelen. (finance). Daar bedoel ik vooral mee dat je in de totale keten moet kijken wat de verschillende spelers

aan return zoeken. Een raffinaderij/ multinational heeft vele opties om te investeren en heeft een cut-of-point boven hun Cost-of-Capital (WACC), De lokale gemeente investeert in infrastructuur met veel lagere risico's en dus tevreden met lagere returns. Splits het business model dan ook naar gelang hun rol / hun bereidheid risico te dragen.

Open vraag: *Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?*

- Dit is allemaal uitgelegd tegen de achtergrond van het businessmodel van het warmtenet in Zuid Holland. Er moet een breder samenwerkingsverband getrokken worden. Er moet een duidelijke leverancier komen die een product levert waarvoor hij iets terugkrijgt. Er moet een tussen partij gecreëerd worden die dit product tot zich neemt in een infrastructuur die hij bereid is zelf te financieren met de daarbij behorende lagere utiliteitsrendementen. Vervolgens wordt dit product geleverd door de tussenleverancier aan de klanten. Hierdoor worden verantwoordelijkheden, risico's en rendementengespreid over meerdere partijen die ze vaak zelf niet alleen willen dragen. (redundancy planning & ownership).
- De ringleiding of (H2 backbone is belangrijk). Een ringleiding is heel handig, want bijvoorbeeld als de regio Rotterdam niet zou leveren dan zou Chemelot of regio Limburg nog wel kunnen leveren aan deze ringleiding en dat het systeem op druk blijft. Dit zorgt ervoor dat waterstof producenten altijd kunnen leveren als ze aangesloten zijn aan deze ringleiding. (Asset characteristics & Network typology)
- Daarnaast is de kwaliteit van waterstof van groot belang. Maar hoe moet die gemeten worden? Je wil een uniforme kwaliteit hebben. Waterstof om ketels op te stoken heb je aan een kwaliteit van 99,9% voldoende. Als je het door een membraan wil halen (fuel cells) dan zul je een kwaliteit nodig hebben van 99.999% zuiverheid. Dit zou je kunnen oplossen door bepaalde stations neer te zetten die de zuiverheid vergroten van waterstof met 99,9% zuiverheid. Maar er zijn nog geen uniforme protocollen voor het meten van waterstof, die zouden er wel moeten komen (Industry standards).
- Hierbij moet ook een meetsysteem komen om deze vormen van waterstof af te rekenen. Die van aardgas kunnen we niet gebruiken. H2 wordt gewogen terwijl aardgas volumetrisch wordt gemeten.
- Wie speelt welke rol binnen de waterstofketen en wie is eigenaar van de assets. Scheiding van product en service (leverancier) zou een goede structuur zijn, maar wellicht moet hiernaar gekeken worden.
- Financiële instrumenten eromheen kun je ook op innoveren. Een voorbeeld is de Revolving subsidie. Waarin kapitaal wordt gegeven om op te starten maar uiteindelijk als het project loopt moet dit terug betaald worden. Vervolgens kan dit weer geïnvesteerd worden in nieuwe projecten.

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

Open vraag: *De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Wat is hier de reden hiervoor? Vindt u ze wel relevant?*

1. Customer value: Die is verondersteld, maar die hangt wel erg samen met de kostprijs van waterstof. Je moet snel naar een schaalgrootte die significante kostprijs reductie teweegbrengen. Daarnaast moet ik wel onderstrepen dat een grootte customer value die nog niet zodanig meegenomen wordt dat je naast CO2 ook heel veel andere emissies voorkomt. Roet, stikstof etc zijn emissies die nog niet in geprijsd zijn met andere woorden gezondheid en ook nog geluid.
   Ook moet er gekeken worden naar de tempo waarmee we het energie systeem willen veranderen. We moeten wat pragmatischer zijn, niet alleen investeren in groen maar gewoon op CO2 moeten sturen. Hoe verminder je het snelst CO2, het kan best zijn dat gedaan kan worden door de experimenten van private actoren m.b.t. blauwe ene groene waterstof te subsidiëren zodat we er zo snel mogelijk ervaring mee krijgen.

2. Technologie: Learning cost curve is van belang, maar van de technologieën heb ik wat minder verstand dus daar kunnen anderen je beter mee helpen.
3. Governance - Energy Tariffs: Ja als de CO2 prijs naar de 40-50 dollar gaat dan worden veel waterstof projecten al een stuk aantrekkelijker. Dit is natuurlijk ook besproken in het klimaatakkoord, maar dit is in feite een "contract voor difference" . De partij betaalt dan Het verschil tussen moet betaald worden op het verschil tussen de CO2 bodemprijs en de ETS prijs. Zo krijgen bedrijven meer duidelijkheid, ok als bedrijf moet ik dan of de bodemprijs betalen of de ETS prijs. Een vlakke prijs jaagt de sommigen op de kast omdat er geen rekening gehouden wordt met wie wel en wie niet investeert in CO2 reductie.
4. Government vision: ja dit kan de overheid doen. Momenteel is dit zeker niet het geval. Wiebes heeft vanaf het begin gezegd jongens dit moet gebeuren, jullie zijn betere experts dan ik dus kom maar met de plannen, o en btw ik heb ook geen geld. Er zijn wel veel mensen die vragen neem de leiding, maar dit gebeurt niet. Misschien doet het volgende kabinet dit wel. Maar als kanttekening een groot deel van de industrie is export, dus de binnenlandse markt voor de zware industrie is klein. Dus je wil deze industrie die toch wel een belangrijke banenmotor niet voor de kop stoten. Maar je hebt wel gelijk de overheid is ook een klant. Bijvoorbeeld in de mobiliteit, kunnen ze heel wat voertuigen die eigendom zijn van de staat vervangen met waterstof voertuigen.

Punt 4. Laatste opmerkingen

<u>*Open vraag:*</u> *Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?*

Er schiet me op dit moment niks te binnen. Als ik nog later nog inzichten op doe dan zal ik ze wel naar je sturen.

8.2.2 Interview: [redacted] 19-06-2019

Punt 1. Visie waterstof als energiedrager in Nederland van interviewde

<u>*Open vraag:*</u> *Wat is uw visie voor waterstof als energiedrager in Nederland.*

Waterstof heeft een duidelijke toekomst, het is al eerder een hype geweest met name in de transportsector. Steeds meer partijen maken investeringen, waaronder landen en ik denk dat dit door gaat zetten. Al zullen veel projecten niet concurrerend zijn uit zichzelf op de korte termijn. Dat gaat nog wel echt 10-15 jaar duren.

Waterstof is één van de weinige opties voor CO2 vrije verbranding, indien het wordt opgewekt met duurzame elektriciteit door middel van elektrolyse. Vooral in de industrie waarbij het verbranden van moleculen nodig is. Hierbij komt ook dat duurzame energiebronnen zorgen voor een toename van fluctueringen in het elektriciteit netwerk. Om deze fluctueringen op te vangen is opslag nodig, die momenteel niet door batterijen vervuld kan worden. Grote hoeveelheden energie kun je wel opslaan met waterstof. Ook een belangrijke rol die waterstof speelt is in de bebouwde omgeving, met name daar waar nul-op-de meter moeilijk te realiseren is, bijvoorbeeld in de bestaande oude woningvoorraad. In het transport zal vooral het zware transport gebruik maken van waterstof.

<u>*Open vraag:*</u> *Wat verandert er als waterstof geïntegreerd wordt in het Nederlandse energiesysteem?*

Knelpunten met net- aansluitingen moeten worden opgelost, dit zou kunnen door waterstof voor opslag te gebruiken. Hiernaast zullen er meer producten op de markt komen waaronder waterstof ketels, die moeten ook ergens op aangesloten worden. Gasleidingen kunnen worden hergebruikt, voor het transport van waterstof.

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

<u>Open vraag:</u> *Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland?*

We zijn niet zelf bezig met projecten. We zijn nu wel net bezig met de beoordeling voor de waterstof tender. Partijen kunnen zich daarop inschrijven met hun project. Daarna worden deze projecten intern bij RVO beoordeelt, vervolgens is de uiteindelijk toetsing van deze projecten door een groep externe specialisten. Deze specialisten geven een ranking aan, hier wordt een vergadering over gehouden en de meest veelbelovende projecten die krijgen subsidie. Het subsidie plafond is €2.2 miljoen, er is voor €8.8 miljoen aangevraagd, maar een kwart zullen worden toegekend wat ongeveer vijf projecten zijn. Met deze tender is breed ingestoken, we zoeken projecten voor productie van waterstof, opslag van waterstof, en bepaalde toepassingen van waterstof in de mobiliteit en de bebouwde omgeving.

<u>Open vraag:</u> *Welke elementen worden er gebruikt om de businessmodellen voor deze projecten te ontwerpen/toetsen?*

Wij toetsen deze projecten op een aantal factoren.
- Ten eerste wat is de probleem- en doelstelling van het project, het resultaat van het project, en de strategie voor het project;
- Financiële aspecten zoals: financiering, omzet, winstmarge, kostenverlaging, extra werkgelegenheid;
- Kennisoverdracht en intellectueel eigendom
- Aantal deelnemers in het project en hun taakverdeling, project risico's

<u>Open vraag:</u> *Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?*

De slaagkans in de Nederlandse markt en maatschappij wordt getoetst aan de hand van:
- Technisch werkend, kan het project goed worden aangesloten op technologische infrastructuren en systemen;
- Commercieel werkend, heeft het project een geschikt en duurzaam verdien model in productie- en waardeketens;
- Juridisch en institutioneel werkend, is het project toelaatbaard volgens de wet- en regelgeving en passen bij standaarden, protocollen en codes;
- Maatschappelijke werkend, wordt het project geaccepteerd door gebruikers of degenen die de gevolgen van de innovatie ondervinden.

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

<u>Open vraag:</u> *De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Wat is hier de reden hiervoor? Vindt u ze wel relevant?*

1. Overheidsvisie: TKI nieuw gas bezig met een meer jaren plan te schrijven samen met ministerie van EZK waarin als het goed is een overkoepelende visie wordt gegeven. Er zijn ook wel tegenstanders van waterstof, die wel goede argumenten hebben. Er moet alleen uiteindelijk wel een richting gekozen worden die praktisch haalbaar is.
2. Tariefstructuur: Ik denk wel dat je een CO2 beprijzing nodig hebt. Wat de precieze hoogte van zo'n tarief moet zijn is moeilijk te zeggen, op een gegeven moment was de CO2 prijs rond de €5-6, dat is dan wel weer te laag.
3. Ownership & access: ik ben op dit gebied geen expert, maar ik denk dat hier wel wat moet veranderen. Omdat nu vaak bepaalde partijen investeringen maken, maar het voordeel van deze

investeringen komt niet altijd terecht bij de partijen die investeren. Bijvoorbeeld, een project waarbij gekeken wordt naar de mogelijkheid voor een elektrolyser op een boorplatform. Hier was één van de aandachtspunten dat de investerende partijen erachter kwamen dat ze vooral bezig waren met het oplossen van problemen voor TenneT. Veel partijen hadden dus al snel zoiets van… tja als wij investeren krijgen we niet de volle voordelen van het project. De value chain optimalisatie van is niet hetzelfde als de optimalisatie van één bedrijf.

4. Contracts for differences in costs: Ja ik denk dat het wel een goed idee is om hiernaar te kijken en te onderzoeken. Een voorbeeld is de SDE+ en de verbreding daarvan. Je kan dit alleen niet oneindig doen, het moet ook niet de enige prikkel zijn om dan toch te investeren.

Punt 4. Laatste opmerkingen

<u>Open vraag:</u> Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?

Er schiet me op dit moment niks te binnen. Als ik nog later nog inzichten op doe dan zal ik ze wel naar je sturen.

8.2.3 [redacted] 20-06-2019

Punt 1. Visie waterstof als energiedrager in Nederland van interviewde

<u>Open vraag:</u> Wat is uw visie voor waterstof als energiedrager in Nederland.

Ik zal zelf de vraag wat breder stellen. Waterstof is niet alleen een energiedrager maar ook een grondstof. De kracht van waterstof ligt in het feit dat het een energiedrager is, maar het kan ook ingezet worden als een grondstof voor de chemische industrie of voor het produceren van synthetische brandstoffen, en als derde het vervult een belangrijke systeemfunctie.

De systeemfunctie houdt in dat je met waterstof in staat bent om van elektriciteit moleculen te maken. Dit is heel interessant want dan kun je af van hoogwaardige fossiele energiedragers. Omdat je die eigenschappen kan nabootsen komende van elektriciteit. Daarbij komt ook dat waterstof kan gebruiken voor het opslag en transport van grote hoeveelheden energie. Duurzame energiebronnen zorgen voor een toename in variabiliteit in het energiesysteem, dit kunnen we prima voorspellen maar dit zorgt wel voor een uitdaging om vraag en aanbod op elkaar af te stemmen. Daar kan de productie van waterstof met elektrolyse veel mee kan helpen. Omdat je heel simpel elektrolysers harder en zachter kan zetten. Daar waar infrastructurele bottlenecks zijn, bijvoorbeeld onvoldoende hoogspanningsleiding aanwezig zijn, zou je energie in de vorm van waterstof door leidingen kunnen transporteren. (system architecture)

Dit zal zich langzaam maar zeker gaan ontwikkelen. In het verleden hebben we al geprobeerd waterstof in te zetten in de mobiliteit. Maar nu proberen we veel meer te doen dan waterstof op 1-dimensionaal niveau te implementeren. De komende 30 jaar zal dit langzaam maar zeker groeien, tot 2030 zal het gebruik van waterstof langzaam opschalen, hierna zal een sterke marktintroductie plaatsvinden tot 2050. Als eerste heb je een markt nodig die bereid en in staat is om hogere prijzen te betalen dan kan de productie gestaag mee groeien.

<u>Open vraag:</u> Wat moet er volgens u veranderd worden om waterstof te integreren in het Nederlandse energiesysteem?

Er moeten een aantal dingen gebeuren. Het eerste en allerbelangrijkste is dat er een serieuze vraag naar waterstof gaan ontstaan, als die vraag kant er niet is zal de productie ook niet op gang komen. Want voor degenen die dan moeten investeren aan de productie kant, is het risico van die investeringen dan te groot. Je moet gewoon afzet hebben. (Finance)

Dit kun je mogelijk maken door allerlei knelpunten die deze introductie in de weg staan weg te nemen. Één van deze knelpunten ligt op intentioneel vlak, bijvoorbeeld beleid. Beleid zal de inzet van waterstof moeten ondersteunen, dit kan door verschillende soorten subsidie ondersteund worden. Een subsidie op elke kilogram waterstof die je koopt; een aanschaf subsidie op het product dat je gebruikt, een fabriek, gasturbine, bus, auto, waterstofketel; het kan zijn een verlaagd accijnstarief; het kan zijn een verlaging van motorrijtuigenbelasting. (governance)

Hiernaast komt ook dat veiligheid en standaardisatie geregeld moeten worden. Je kan gerust met 1 bus rijden, maar wat als er nu 1000 bussen en vrachtwagens op waterstof gaan rijden, kunnen die allemaal tanken, is de veiligheid hiervan gegarandeerd. Hoe zit het met kosten en afrekening. Dit zijn waar nog naar gekeken moet worden. (Standardisation)

En om de belofte van waterstof volledige te kunnen leveren moet er ook genoeg duurzame energie zijn om groene waterstof te produceren. Het potentieel is ongeveer 60 GW op de Noordzee en nog maar beperkt ruimte op land. Terwijl we ongeveer nog drie keer zoveel nodig hebben, import zal altijd nodig zijn.

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

<u>Open vraag:</u> Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland?

Ik ben van [redacted] en we houden ons eigenlijk niet bezig met projecten. We zijn bezig met een programma te maken, onder andere het meerjarenplan. Maar dit programma geeft de ruimte aan projecten op subsidie en ondersteuning te krijgen. Wij faciliteren ontwikkeling en kennisuitwisselingen en het hele spel rondom waterstof innovatie.

<u>Open vraag:</u> Ok dan stel ik de volgende vraag iets anders. Welke elementen/factoren vindt u belangrijp waar businessmodellen van een waterstof projecten op afgerekend kunnen worden.

Ik denk dat het allerbelangrijkste is de vraag kant. Ligt er een solide vraag onder een productie business case. Daarbij moet ook de business case voor waterstof projecten goed vergeleken worden met de alternatieven. Over de gehele breedte op kost niveau. Als je een tramlijn aan wil leggen kost dat miljoenen soms wel honderden miljoenen, wat zijn de kosten om een dedicated buslijn aan te leggen waar waterstof bussen overheen rijden? (Product/service)

Het tweede is betrouwbaarheid van de technologie. Is de technologie betrouwbaar genoeg om ook langdurig ingezet te worden voor het doel waar het bestemd voor is. Bij een nieuwe innovatie is dit best lastig maar wel cruciaal. Je wil niet dat de technologie gedurende gebruik te maken krijgt met storingen of ongelukken. (Technology)

Het derde is wat vindt de maatschappij ervan. Wat je met ook met waterstof doet, die projecten moeten maatschappelijk getest zijn voor blauwe waterstof is natuurlijk de discussie rondom CCS. Het voorbeeld uit Noorwegen waar vorige week een waterstof tankstation is ontploft. Hoort bij een innovatie, gelukkig geen gewonden of doden, dit hebben ze goed aangepakt. Iedereen heeft gezegd we gaan even met alles stoppen, eerst even uitzoeken wat er aan de hand is, als we dit weten dan kunnen we maatregelen nemen. Dit soort incidenten moet je serieus nemen. (Customer value)

<u>Open vraag:</u> Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?

Systeem: Snelle hulp bij storingen en incidenten. Als dit niet gebeurt en een project wordt volledig in de soep gedraaid dan krijgen alle opeenvolgende projecten daar last van met de financiering. Wettelijk kaders betreffende hoe waterstof geclassificeerd is. Als waterstof nog wordt behandeld als een industrieel product dan zijn de veiligheidsgrenzen voor een waterstof tankstation veel hoger dan voor een diesel of lpg-tankstation. (Control mechanisms)

Markt: Overheid moet het beeld scheppen dat ze vertrouwen hebben in waterstof. Dit schept vervolgens ook vertrouwen in de markt. Bij de bedrijven en bij de consumenten. (Formal institutions). Hierbij komt ook dat er een bepaalde vorm van toezicht moet komen op het uitvoeren van de standaardisatie en veiligheid. (Organisation). Kostprijs is ook belangrijk. De overheid kan ervoor zorgen dat de kostprijs van waterstof niet al te hoog wordt.

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

Open vraag: De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Vindt u ze wel relevant?

1. Business model (Organisation, value exchange, process alignment)
   Zijn vanzelfsprekend, dit moet goed geregeld worden binnen een project. Projecten moeten samenwerken met actoren in de waardeketen.
2. Businessmodel (information exchange): Dit zal in de volgende fasen van de projecten meer gebeuren. Nu is het vaak nog een gelegenheid studies. De partijen stoppen er enkele tienduizenden euro's in en vertienvoudigen dit in waarde door overheidssubsidies. In de volgende fase zul je zien dat partijen miljoenen moeten investeren in het project en dan komt er een op rationalisatie slag. Dan wordt er ook een projectmanager op gezet die een mandaat heeft. Als er een risico gepaard gaat met investeringen dan zitten de organisaties erboven op.
3. Design principles & governance: Network typology: Access, Ownership.
   Niet erg belangrijk voor de beginnende transitie. Sommigen zeggen dat je een publiek netwerk nodig hebt in de haven van Rotterdam. Waarom dan? Als er schappelijke tarieven zijn, en verschillende diensten ingekocht kunnen worden wat is dan het probleem? Dan kunnen partijen toch zelf beslissen of ze toegang willen?
   Laat de markt maar beslissen, hoeft niet hetzelfde geregeld te worden als het huidige aardgasnetwerk. Als er een schappelijk tarief komt dan kan er later besloten worden om delen van het netwerk nog publiek te maken zodat iedereen er toegang tot heeft. Zo kunnen nieuwe delen van het gas netwerk die moet komen via een tender proces geprivatiseerd worden. Dit stimuleert ontwikkeling van de energie transitie. Denk creatief na over wat nodig is en wat mogelijk is!
4. Governance: energy tariffs
   Hoeft niet per se, bodemprijs voor CO2 is wel ok. Maar het ETS-systeem werkt. Er moeten alleen minder rechten om CO2 uit te stoten uit gegeven worden. Ons primaire doel is de opwarming onder 2 graden Celsius houden, een goede manier is om CO2 uitstoot te belasten. Wat dit tarief moet zijn is lastig te zeggen. Dit systeem werkt erg goed als primaire prikkel voor bedrijven om wat te doen aan hun uitstoot.
5. Organization: Energy / Gas codes
   Zeker erg belangrijk. Er moet beleid komen voor de kwaliteit van waterstof. Je weet wel wat voor gas kwaliteit er nodig is om het in een brandstofcel of gasturbine te stoppen. Dit is alleen nog niet duidelijk voor waterstof pijpleidingen. Als je veel aanbieders en vragers aangesloten hebt op een netwerk heb je natuurlijk geen uniform eind gebruik van het gas. In zekere zin zijn de partijen die aangesloten zijn op het netwerk bepalend voor de kwaliteit van waterstof dat erdoorheen gaat. Uiteindelijk moet er wel consensus komen over de kwaliteit van waterstof die door een landelijk netwerk gaat. Ook de bemetering en afrekening van dit gas moet nog bepaald worden.

Punt 4. Laatste opmerkingen

Open vraag: Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?

Het ecosysteem rond waterstof heeft zich ontzetten snel ontwikkeld. Voor duurzame energiebronnen begonnen de activiteiten op kleine schaal en pas na een tiental jaren begonnen de grote partijen zich ermee te bemoeien. Bij waterstof daarentegen wordt op elke schaal gekeken naar mogelijkheden. Van kennisinstellingen, multinationals, overheid, netwerkbeheerders tot het individueel gebruik. Dit is verbazend en gebeurt niet zo vaak. Een kanttekening is wel dat we er nog lang niet zijn er moet nog veel gebeuren.

8.2.4 [redacted] 18-06-2019

Punt 1. Visie waterstof als energiedrager in Nederland van interviewde

<u>Open vraag:</u> <u>Wat is uw visie voor waterstof als energiedrager in Nederland</u>.

Mijn verwachting is dat waterstof voor grote energie slurpers zoals de industrie en misschien ook zware mobiliteit de brandstof van keuze gaat worden. En op die manier traditionele fossiele brandstoffen gaat vervangen. Waterstof zal mogelijk ook doormiddel van opslag in cavernes om het energiesysteem te balanceren met name om seizoen fluctuaties op te vangen.

<u>Open vraag:</u> <u>Wat moet er volgens u veranderd worden om waterstof te integreren in het Nederlandse energiesysteem</u>?

Ik denk dat het Nederlandse energiesysteem nog niet is uitgelijnd om energie conversies makkelijk mogelijk te maken. Technisch kan het, maar vooral regulatoire gezien zijn er wat beperkingen in de rollen die spelers zoals Gasunie en TenneT hebben. Daar is werk aan de winkel nodig om meer de systeemintegratie rol ook mogelijk te maken. Of deze rol vervuld moet worden door een landelijke net operator of dat dit vervuld moet worden door commerciële partijen dat laat ik even open. Maar ik merk dat we nog erg in de ouderwetse verdeling zitten betreffende de gas en elektriciteit infrastructuur terwijl waterstof deze twee infrastructuren beter met elkaar zou moeten kunnen verbinden.

Daarnaast zal het ook helpen als op de stroommarkt een soort van capaciteitsdienst aanwezig zou zijn. Bijvoorbeeld in de gasmarkt wordt er extra capaciteit aangeboden is als er een tekort is aan gas, dit is bijvoorbeeld wat GasUnie doet met de aardgas opslag in Zuidwending. Maar zover mij bekend is een soortgelijke dienst voor de elektriciteitsmarkt nog niet mogelijk, terwijl waterstof daar een kans zou hebben. Op die manier zou je dus grote hoeveelheden waterstof kunnen opslaan en kunt inzetten als er een onverwachte stroom tekort zou plaatsvinden. Of als er een enorme hoeveelheid stroom overschot is dan kan die energie worden omgezet naar waterstof door middel van elektrolyse.

Voor blauwe waterstof moet het grootschalige afvangen, hergebruik en/of opslag van CO2 mogelijk zijn, wat op dit moment nog niet technisch kan. Hiernaast is de CO2 prijs nog te laag om dit attractief te maken voor partijen om hierin te investeren. Daarentegen als de CO2 prijs hoog zal zijn zal het al snel blijken dat de productie van blauwe waterstof de meest efficiënte manier is om emissiereductie toe te passen.

Tot slot denk ik dat de huidige kostprijs van duurzame energie bronnen nog niet op het niveau zijn dat groene waterstof competitief is. Maar dit is niet iets wat momenteel nog actief gestuurd kan worden, dit is meer een marktontwikkeling die gaande is.

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

<u>Open vraag:</u> <u>Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland</u>?

1. Het meest zichtbare project is het project [redacted] waar wij bezig zijn in een consortium van acht partijen uit de industrie, mobiliteit en overheid. Om te kijken of we een oude [redacted] locatie kunnen hergebruiken om een soort waterstof hub te maken. Met hub bedoel ik dat we groene waterstof wordt geproduceerd uit groene energie die voornamelijk afkomstig is van een PV zonnen

park op dezelfde locatie. De waterstof wordt afgezet in zowel mobiliteit (bussen, open vervoer) als in de industrie. Op deze manier hebben we een soort van knooppunt met meerdere toepassingen.

2. We hebben ook een project (haalbaarheidsstudie) in [redacted] waar het doel is om een nieuwbouwwijk op waterstof te laten draaien. Waarbij we verkennen of de bestaande vergunningsruimte die aanwezig is bij een oude [redacted] locatie voor toepassingen met gas kan ingezet worden voor waterstof projecten. Dit maakt het makkelijker om waterstof toepassingen te landen op een oude industriële locatie met alle faciliteiten die je nodig hebt om dit te doen.
3. Het derde project is een project waarin we met een consortium bezig zijn met de haalbaarheid om een bestaand gasplatform om te bouwen naar een electrolyzer te verkennen.

Open vraag: Welke elementen/factoren vindt u belangrijp waar businessmodellen van een waterstof projecten op afgerekend kunnen worden.

1. Winstmarge is een de voornaamste, we zijn natuurlijk een commercieel bedrijf. Wellicht in bredere zin of er uitzicht is op winst/business op termijn. De reden waarom ik dit zeg is omdat we nu de projecten ook nog zien als pilots/onderzoekprojecten om kennis op te doen over hoe de markt en het systeem werkt en hoe deze twee zich vervolgens kunnen gaan ontwikkelen. Welke partijen bijvoorbeeld in een bepaalde regio die energie transitie samen mogelijk willen maken.
2. Schaalgrootte is ook van belang voor een groot bedrijf zoals [redacted] We zijn een groot bedrijf hierdoor hebben we een bepaalde schaal nodig voordat een project aantrekkelijk genoeg is. Dit heeft wat nadelen maar komt ook met wat voordelen. Als die schaalgrootte er is en wij gaan een project ontwikkelen dan leveren we de benodigde projectorganisatie, middelen en kennis om de projecten ook grootschalig uit te voeren.

Open vraag: Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?

- Systeem
  1. Er moet een samenwerking komen van actoren aan de elektriciteit én gas kant. De oplossing voor een probleem van één van de actoren hoeft niet direct een probleem te zijn voor andere actoren. Zo zou het kunnen zijn dat een hele mooi oplossing niet ontwikkeld wordt.
  2. Daarnaast proberen we de elektriciteitsmarkt goed in kaart te brengen. Om een gevoel te krijgen van de verwachte opwekking en prijs. Een voorbeeld is dat Duitsland verleden jaren regelmatig windparken heeft stopgezet omdat er een overflow van duurzame energie was. Dit zijn factoren die we meenemen voor de inschatting van een project in Nederland die dit kan oplossen of hier mogelijk ook van kan profiteren.
  3. De congressie in delen van Nederland is ook een belangrijke factor die we meenemen. Bijvoorbeeld in Emmen kunnen geen zon of windparken meer aangesloten worden omdat het elektriciteitsnetwerk overbelast is.

- Markt
  1. Zoals eerder vermeld op het gebied van beleid, met name ownership van infrastructuur en risicospreiding.
  2. We houden in de gaten hoe de subsidieregelingen zicht ontwikkelen. Met name de SDE++, het kan zijn dat waterstof gezien wordt als interessant of dat het afvalt omdat het relatief duur is vergeleken met post combustion CCS.

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

Open vraag: De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Vindt u ze wel relevant?

1. Control mechanisms: Gebeurt al genoeg, al tientallen jaren wordt waterstof geproduceerd voor bepaalde industriële processen. Dezelfde controlemaatregelen kunnen gebruikt worden. Hierin moet wel een onderscheid gemaakt worden tussen de grote gecentraliseerde productiefaciliteiten en de gedecentraliseerde kleinschalige productiefaciliteiten. Je kunt niet dezelfde veiligheidsmaatregelen eisen van de kleine productiefaciliteiten als voor de grotere faciliteiten, gewoon omdat het risico kleiner is.
2. Market design - Formal institutions (Overheidsvisie): volgens mij is die visie er al wel. Het is al duidelijk wat de overheid wil qua CO2 reductie in een aantal sectoren, dit kun je vinden in het klimaat akkoord. De invulling hiervan moet door de markt geregeld worden. Ik ben niet van mening dat de overheid moet beslissen het moet waterstof worden.
3. Market design - Governance & Design principles (Ownership & Acces): Volgens mij kan waterstof transport op nationaal niveau hetzelfde geregeld worden als het transport van aardgas op dit moment. Wat er ontbreekt is een stukje integratie, op het gebied van access zouden partijen meer vrijheid moeten krijgen om een propositie te maken voor de koppeling tussen het gas en het elektriciteit netwerk.
4. Market design - Governance (gas quality standards): Ja volgens mij is dit werk in uitvoering, net zoals voor aardgas zal je voor waterstof kwaliteitseisen moeten stellen, met name als je het publieke net in gaat. Stel dat het allemaal in privaat beheer is dan is het aan deze partijen zelf.
5. Market design - Organization (finance): de overheid speelt hier naar mijn mening geen cruciale rol in.
6. Businessmodel (technology): De functionele eisen zijn wel belangrijk ja.
7. Businessmodel (information exchange): Erg belangrijk in huidige projecten. Hier zijn we veel mee bezig, met name in de haalbaarheidsstudies en pilots die de voornaamste rol hebben om kennis te genereren en te delen. Dit maakt het mogelijk om een waterstof markt te bouwen.

Punt 4. Laatste opmerkingen

Open vraag: Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?

Ik denk dat als je het hebt over waterstof dat je niet alleen de Nederlandse kant moet behandelen maar dat we binnen Europa een bredere context hebben. Ook omdat het gas en het elektriciteit netwerk in Europa volledig gekoppeld zijn. Ik denk dat het waardevol is om een iets bredere uitstap te maken, in de zin van wat betekent waterstof voor de west-europa.

Waterstof is ook geen doel maar een middel tot energie transitie. Dit middel kan op bepaalde plekken misschien minder van toegevoegde waarde zijn als dat we denken, maar dit zullen we vanzelf zien.

8.2.5 Interview: [redacted] 28-06-2019

Punt 1. Visie waterstof als energie drager in Nederland van interviewde

Open vraag: *Wat is uw visie voor waterstof als energiedrager in Nederland.*

Laat ik vooropstellen dat ik in niet een visie heb voor waterstof als energiedrager in Nederland die anders is dan voor de rest van de wereld. Mijn rol binnen [redacted] is kijken naar welke technologieën met toepassingen in

Nederland of daarbuiten processen goedkoper en efficiënter maken. Mijn mening is dat op welke plek dan ook dat dit heel belangrijk is. Dat kan gaan over een energiedrager zoals elektriciteit maar het geldt ook voor waterstof.

<u>*Open vraag:*</u> *Wat verandert er als waterstof geïntegreerd wordt in het Nederlandse energiesysteem?*

Deels heeft het te maken met hetgeen hierboven, nu is waterstof wel beschikbaar maar vergeleken wat we nu op grote industriële schaal doen is het vrij duur om waterstof met renewables en elektrolyse op te wekken. Natuurlijk één van de dingen die hierbij kan helpen is de kosten op laag te brengen. Dit is wel makkelijker gezegd dan gedaan op korte termijn en voor grote schaal. Met name voor de industrie moet er een belangrijke drijfveer zijn voordat ze hun activiteiten gaan veranderen. Of dat via regelgeving moet gaan of via bepaalde heffingen dat laat ik aan degenen over die dat als specialisme hebben.

Dat gezegd hebbende moet er een verbetering komen in hetgeen wat we aanbieden en wat er wordt gevraagd. Nou is natuurlijk net vandaag het klimaatakkoord gepresenteerd een uur geleden. Er gebeurt dus al wel wat maar er moet nog wel veel gedaan worden.

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

<u>*Open vraag:*</u> *Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland?*

Over een paar kan ik je niks vertellen want die zijn geheim. De projecten waar ik je wel over kan vertellen zijn voornamelijk technologie scouting projecten. Dit betekent dat we een aantal challenges, bv. [redacted]. Die wordt opgezet vanuit Nederland maar dan doen ook bedrijven vanuit de rest van Europa en zelfs de wereld aan mee. We hebben ook een soortgelijke challenge die vanuit de V.S. is opgezet, waar voornamelijk bedrijven uit Amerika aan meedoen maar ok een paar niet Amerikaanse bedrijven aan mee.

Wat we in die challenges doen is aan start-ups en kleine bedrijven, die net een paar jaar bezig zijn met een specifieke technologie, vragen om deze technologieën te verbeteren. Bijvoorbeeld het bouwen van betere elektrolysers of een andere waterstof drager te ontwikkelen. Binnen deze challenges worden een aantal veelbelovende bedrijven uitgekozen en die worden verder geholpen. Het voordeel voor ons is dat wij hun, hun kennis en hun technologie goed leren kennen. Kunnen vaststellen of de technologie beter is dan wat we al hebben. Als we dan beslissen om samen te werken wat ze van ons nodig hebben, geld, tijd, een locatie, expertise, of het testen van de technologie. Als ze verder komen in de challenge en we gaan samenwerken dan bouwen we bijvoorbeeld een prototype met de start-up.

<u>*Open vraag:*</u> *Welke elementen worden er gebruikt om de business modellen voor deze projecten te ontwerpen/toetsen?*

Ik ben niet degene die naar de business case kijkt, ik kijk meer naar de technologische aspecten van de business case. We hebben ook teams voor als Shell echt een investering wil gaan doen. Vaak presenteren teams veel claims qua technologie, maar dit zijn vaak geen garanties maar ambities. Ik probeer het 1 van het ander te scheiden.

Binnen deze projecten zijn voornamelijk belangrijk (zie vorige vraag)

- Information exchange
- Value exchange
- Technology
- Finance

<u>Open vraag:</u> *Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?*

Sommige van de technologieën die wij ontwikkelen, kun je de oude technologie uit het systeem halen en de nieuwe technologie inzetten, de rest van het systeem blijft hetzelfde. Een voorbeeld hiervan is een nieuwe compressor.

Voor andere technologieën, als je bijvoorbeeld van gasvormige waterstof over gaat naar een waterstofdrager dan zit de waterstof ergens aan vast. Dan is voor en na transport een transformatie slag nodig. Dus dan moet je een extra activiteit voltooien om je moleculen te krijgen en een extra stap is nodig om waterstof weer op de juiste druk te krijgen waar je systeem voor is ontworpen. Bij dit soort opstellingen wordt er dan gekeken of dit nou echt een vooruitgang is of is dit iets wat alleen succesvol kan zijn met een nieuwe infrastructuur. Met deze tweede optie hoeft het niet gelijk een no-go te zijn, maar dan moet er wel extra voordelen zijn die het de moeite waard maken om de technologie te ontwikkelen. Ook omdat het systeem dat je verandert, een fabriek of station, een tijdje stilligt wat voor klanten vervelend is.

Verder zijn er vanuit beleid ook nog heel veel dingen die belangrijk zijn. Met name de veiligheid en de 'perceived' (gevoelde) veiligheid zijn erg belangrijk en die komen niet altijd overeen. Er kan een bepaald veiligheidsniveau gehaald worden maar dit hoeft niet te zijn dat de gebruiker dit ook zo voelt. Daar moet het één of andere nog verbeterd worden, dit is een deel gewenning maar kan bevorderd worden door informatie te delen.

Complementaire goederen moeten ook aanwezig zijn, je kan wel waterstof aanbieden maar bijvoorbeeld in de mobiliteit moeten er dan wel voertuigen zijn die op waterstof rijden.

- Design perspective: Asset characteristics
- Design principles: Redundancy planning
- Control mechanisms: Safety instructions and standards (preventive maintenance)
- Formal institutions & Governance

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

<u>Open vraag:</u> *De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Wat is hier de reden hiervoor? Vindt u ze wel relevant?*

1. Government vision: over het algemeen is er wel redelijk wat aandacht voor waterstof, maar die aandacht is nog oppervlakkig. In het algemeen is waterstof nog niet zo'n bekend fenomeen. Mensen kunnen nog niet goed inschatten wat de voor- en nadelen zijn. Dat moet zich nog ontwikkelen. Bepaalde targets worden gezet, dat is een goed begin, maar daarna moet je verder. Ik weet niet zeker of het altijd aan de overheid is om de visie heel gedetailleerd neer te leggen, of marktpartijen dit samen met de overheid uit kan werken. Subsidie is belangrijk daar maken we vaak gebruik van, maar het is ook belangrijk dat als er een nieuwe regelgeving komt dat die voor een lange tijd blijft staan. Voor de industrie al helemaal, daar moeten partijen eruit kunnen gaan dat de regelgeving een aantal decennia vooruitgaat. Dit blijkt nog wel lastig te zijn voor beleidsmakers. Het belang voor beleidsmakers ligt vaak over een periode van 4 jaar en voor bedrijven over een periode van 10-20 jaar.
2. Ownership: Hier heb ik het niet over gehad omdat we op dit moment in de huidige fase van de markt er nog vrij weinig spelers zijn. Dan kom je al snel in de situatie dat je elkaars concurrent bent, maar eigenlijk in de positie zit dat je nog niet met elkaar wil concurreren. Want je vecht dan met z'n tweeën tegen een veel groter systeem, dus als je elkaar dan gaat bevechten dan komt het geheel niet goed uit. Dus op dit moment werk je met een aantal partijen die op bepaalde vlakken concurrent zijn graag samen. Als op een gegeven moment de markt heel volwassen wordt, dan wordt dit natuurlijk anders. Ownership van assets is wel belangrijk maar de contracten daarom heen en de intellectueel eigendom

daarachter veel belangrijker. Het bezitten van het equipment is niet altijd zo heel interessant, het bezitten van de technologie of de licentie of het recht om iets te verkopen wel.

3. Tariff structue: [redacted] is één van de aanjagers voor een prijs op CO2, niet alleen in Nederland maar over de hele linie wereldwijd, zodat je een gelijk speelveld hebt. Dit kan voor waterstof ook bijdragen maar momenteel is deze prijs schommelend (ETS) en op een punt waar je nog niet op elke plek het produceren van waterstof kan laten concurreren met aardgas. Voor de rest is de waterstof prijs nu gekozen, dit ligt op een punt waarvan men denkt ongeveer uit te komen met de kosten. Hier moet uiteindelijk wel een marktmechanisme op komen zodat winsten behaald kunnen worden. Daar is de markt daarentegen nu nog te jong voor.
4. Industry standards: absoluut belangrijk[redacted] zit ook in veel van de samenwerkingen die de standaarden maken. Dit zijn standaarden die gaan over kwaliteit, veiligheid, of marktsegmenten die nog niet bestaan. Of hele praktische dingen zoals of je met een auto in een tunnel of parkeergarage mag komen. Zulk soort dingen moeten uitgezocht worden.
5. Product/Service: ook belangrijk, maar ook de maatregelen die worden genomen om het product te leveren. Bijvoorbeeld de grote investeringen die worden gedaan om de kwaliteit van waterstof te meten en zo te garanderen dat die waterstof jouw auto niet beschadigt.

Punt 4. Laatste opmerkingen

<u>Open vraag:</u> Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?

Elektriciteitsopwekking met waterstof (Fuel cell centrale) is interessant omdat dit in het oude systeem niet kon doen. Omtrent de ontwikkeling van fuel cells gaat nog echt veel gebeuren.

8.2.6 Interview: [redacted] 02-07-2019

Punt 1. Visie waterstof als energie drager in Nederland van interviewde

<u>*Open vraag:*</u> *Wat is uw visie voor waterstof als energiedrager in Nederland.*

Waterstof is nu al een belangrijke grondstof in de Nederlandse industrie. Met de toenemende druk op CO2 uitstoot en de kosten die daar mee gemoeid zijn zal het gebruik van waterstof in Nederland toenemen. Omdat het een alternatieven gaat vervangen, met name omdat waterstof uiteindelijk groen geproduceerd kan worden. De randvoorwaarden in Nederland staan toe dat we relatief snel het energiesysteem kunnen veranderen, maar dat uiteindelijk de waterstof economie, net zoals de hele energiewereld, een 'connected' wereld blijft. Dit betekent dat er ook een mondiale markt zal ontstaan, met directe connecties naar Duitsland, België, Verenigd koninkrijk en Denemarken. Waterstof wordt nu op industriële eilanden gebruikt, de clusters om zo maar te spreken, en wordt gewonnen uit aardgas. Op het moment dat je waterstof gaat vergroenen en in toenemende mate als energiedrager gaat gebruiken, dan verwacht ik dat die markt verbonden is met de rest van de wereld.

Nederland met een vrij sterk op fossiel gebaseerde economie een belangrijk energie en economische transitie moet doormaken om de CO2 doelstellingen te kunnen halen, waterstof kan daar een grote rol in spelen maar dat is een ondersteunende rol.

Een visie moet alleen niet een doel op zichzelf zijn, een eind klant naar op zoek is, is energie. Welke drager daarvoor gebruikt wordt, zullen voor de meeste klanten een worst wezen. Wat belangrijker is: of dat een betrouwbare bron van energie is; CO2 neutrale bron van energie; is het een betaalbare bron van energie.

Open vraag: *Wat verandert er als waterstof geïntegreerd wordt in het Nederlandse energiesysteem?*

Huidige productie van waterstof wordt allemaal gemaakt vanuit aardgas. Het wordt gebruikt in raffinage, kunstmestproductie en chemie. Dit zijn allemaal industrieën die Nederland wil behouden, dus dat is je eerste grote markt en daar zitten ook je grote volumes. Daarnaast heb je ook een warmtevraagstuk dat je moet oplossen. Op dit moment worden veel processen in de industrie, en ook onze huishoudens natuurlijk, voornamelijk met gas verbranding verzorgt. Dit zorgt voor CO2 uitstoot dus daar moet je vanaf. Een mogelijk alternatief is waterstof voor verwarming met name de hoge tempratuur verwarming. Lage tempratuur verwarming zijn meerdere en ook goedkopere alternatieven voor bijvoorbeeld warmtepompen en geothermie. Maar voor de hoge temperatuur industriële processen is waterstof een goede kandidaat voor verduurzaming. Dit is een markt dat dat gekenmerkt wordt door high volume-low margin.

Nu als je ook naar het klimaatakkoord kijkt dan zie je ook dat waterstof in de mobiliteit erg gestimuleerd gaat worden. Als ik de getallen in het klimaatakkoord volg dan zal waterstof in de mobiliteit sneller groeien dan elektrische mobiliteit in de afgelopen 10 jaar. Dat noem ik ambitieus, maar het is ontegenzeggelijk zo dat waterstof in vergelijking van batterij elektrische voertuigen het voordeel heeft van ‘range’. Dus zeker als je naar zwaarder transport kijkt en voorspelbaar transport, zoals bussen, denk ik dat er een goede basis gelegd kan worden voor waterstof in de mobiliteit. Het zou kunnen dat we in de toekomst allemaal waterstof tankstations gebruiken in plaats van laadpalen, dat zal de tijd leren. Mobiliteit is typisch een high margin-low volume markt.

Hetzelfde geldt voor huishoudens, de warmtevraag in huishoudens verduurzamen is een lastige opgave. Er zijn een paar opties voor handen, één daarvan is waterstof. Dit zou op twee manieren kunnen, je zou in een wijk een warmtenet kunnen creëren, en die warmte middels verbranding van waterstof te verzorgen. In Hoogeveen zijn we bijvoorbeeld aan het kijken naar waterstof cv-ketels. Het aardige van dit idee is dat je een 1 op 1 parallel creëert met het huidige aardgas gedreven systeem. Als die vraag er is dan zal de productie vanzelf wel op gang komen. Hoe je die markt ordent en opstelt is wel een belangrijk vraagstuk en daar zal wel het 1 en ander moeten veranderen. Daarnaast moet er ook meer duurzame energiebronnen bij gebouwd worden. We willen naar 11,5 GW windenergie in 2030, dan heb je pas genoeg duurzame energie om grootschalige groene waterstof te produceren. Dan moet ook nog een balanceer probleem opgelost worden, hoe stem je vraag en aanbod goed op elkaar af. Moet dit met opslag in de vorm van zoutcavernes of in oude gasvelden. Of moet dit door importeren van groene waterstof van elders in de wereld. De systeem vraagstukken zijn belangrijk, er moet goed over nagedacht worden hoe dit opgelost kan worden maar deze vraagstukken kun je niet in isolatie behandelen.

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

Open vraag: *Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland?*

Elektrolyse project [redacted], daar hebben we nu een Europees subsidie aanvraag op lopen. Die we hopen te krijgen. Als we die krijgen kunnen we op de niet al te lange termijn over gaan op een investering.

Het project in [redacted]. Een nieuw te bouwen woonwijk naast een oude [redacted] locatie en die locatie zal dan gebruikt kunnen worden als waterstof overslag en eventueel ook als waterstof productie locatie. Deze nieuwgebouwde huizen worden in dit geval voorzien met waterstof CV ketels. In fase twee wordt dan gekeken naar de mogelijkheden om de omliggende wijken om te zetten van aardgas naar waterstof. Dit project doen we met name om ervaring op te doen met hoe de partnerships werken; hoe het commerciële model in elkaar zit.

Onze ambitie is wel om een grote rol te blijven spelen in het Nederlandse energiesysteem. Daarom zijn we nu ook aan het kijken hoe wij grote additionele volumes voor industrieel gebruik in het systeem kunnen krijgen. En maakt dat de industriële sectoren in Nederland verbonden zijn door een waterstof ring. In eerste instantie kijken we naar blauwe waterstof, blauwe waterstof veronderstelt de opslag van CO2. De [redacted] heeft in

Nederland veruit de grootste offshore opslagcapaciteit voor CO2. Dus dat maakt ons een belangrijke partner voor blauwe waterstof productie, maar daarnaast hebben we ook veel oude locaties die aan het gasnetwerk verbonden zijn. Hier kan je dan ook op verschillende methodes waterstof uit aardgas kunnen winnen. Tot nu toe wordt de conversie van gas naar waterstof op de industriële sites gedaan. Met de conventionele wijsheid was dat logisch. Maar als je de wereld gaat veranderen, dan kan het verstandig zijn om ook naar andere plekken op de kaart te kijken voor waterstof productie.

Open vraag: *Welke elementen worden er gebruikt om de businessmodellen voor deze projecten te ontwerpen/toetsen?*

Dat zijn er heel veel. Wij gebruiken het TECOP-model. Dit staat voor:

1. Technology: laat ik op voorhand zeggen dat de integratie van waterstof niet een technology 'play' is. De technologieën bestaan, het kan natuurlijk beter en efficiënter, maar de integratie zal niet versneld worden door baanbrekende technologieën.
2. Economics (finance): wat bij de economische modellen lastig is dat de olie en gas wereld is een voorspelbare wereld. Niemand kan je vertellen wat de olie en gasprijs is over vijf jaar, maar een realistische bandbreedte kan wel. Alle andere onderdelen, zoals bewegingen in de supply chain, doorlooptijden van projecten is wel goed in te schatten. Dit zijn projecten die we al 100 jaar doen. Als je naar waterstof kijkt dan zijn er best wel wat afhankelijkheden die lastig te voorspellen zijn. Zoals het klimaatakkoord. Het is moeilijk te voorspellen hoe dit akkoord uiteindelijk vormgegeven gaat worden. Een voorbeeld is CO2 beprijzen. Hetzelfde met de elektriciteitsprijs. Om dit goed in te kunnen schatten gebruik je scenario's.
3. Commercial: Factoren die te maken hebben met de markt en marketing van het product.
4. Organization: We werken met nieuwe partners. Welke rol wil je spelen in de value chain, wil je überhaupt wel opereren in de value chain. Wil je alleen midden investeerder zijn.
5. Politics: Alles met betrekking tot de politiek. Beleidsvorming, beleidsvoering en politieke onzekerheid. Nederland is best wel een lastig land om lange termijn business te doen, omdat overheidsbeleid best grillig is. Indirect wat veel interessanter is het maatschappelijk draagvlak voor waterstof. Er is een grote burgerij die betrokken wil zijn bij de keuzes die gemaakt worden over de inrichting van het energie landschap. Het gesprek moet aan gegaan worden met deze groep.

Binnen deze projecten zijn voornamelijk belangrijk (zie ook vorige vraag)

- Finance
- Value exchange
- Technology
- Customer value
- Product/service
- Organization

Open vraag: *Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?*

Aantal zijn al opgenoemd (zie vraag2):

- Design perspective: System architecture & Asset characteristics (decentralized level of production; interdependency gas and electricity market; means of production, transport and storage)
- Design principles: Network typology; production, grid and storage capacity.
- Control mechanisms: Operational coordination (balancing regimes)

- Formal institutions: speed of government government policy making & government vision (klimaat akkoord)
- Governance: access regulation, market regulation, policy; energy tariffs.
- Organization: degree of horizontal & contractual arrangements; degree of horizontal and vertical integration.

Als je naar de hele value chain kijkt, bij blauwe waterstof kijk je dan naar

- Gaswinning
- Conversie van aardgas naar waterstof
- Afvang van CO2 en opslag van CO2
- Levering in een distributie net
- Afnemers

Bij groene waterstof

- Opwekking van duurzame energie
- Elektrolyse
- Groene waterstof in het distributie net.
- Opslagmethoden voor flexibiliteit
- Afnemers

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

<u>Open vraag:</u> *De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Wat is hier de reden hiervoor? Vindt u ze wel relevant?*

1. *Information exchange*:
   Is een interessante, daar kan ik wel wat over uitweiden. Op dit moment doet shell redelijk wat in retail van waterstof. Onze bevinding is dat de huidige autorijder niks uitmaakt welke kleur die waterstof heeft. Dit kan veranderen over tijd, maar op dit moment is het belangrijkste voor de autorijder de kosten en de leveringszekerheid. Op het moment dat er een markt differentiatie ontstaat, dat je andere prijzen kan handhaven voor grijze, blauwe en groene waterstof. Dan moet je gaan trekken aan je product. Dus dan zul je op de een of andere manier een informatiesysteem gaan ontwikkelen dat bijhoudt van de bron is van die waterstof. De noodzaak is er nog niet omdat de klant nog niet dat verschil betaalt. Tussen partners is het ook zeker van belang, vertrouwensbasis is nodig voor een goede samenwerking.
2. *Design principles; Ownership*
   Op dit moment is het de markt nog te jong. Als de markt zich verder ontwikkeld moet de eigendom van delen van de value chain wellicht gereguleerd worden. Op dit moment zijn partijen nog aan het uitzoeken welke rol ze willen nemen in de value chain.
3. *Control mechanisms: Preventive maintenance (Safety instructions and standards); Routines & emergency procedures*
   Heel goed dat die erbij staat. De reden dat ik het niet heb genoemd omdat dit voor ons vanzelfsprekend is. Als we het niet veilig kunnen doen, doen we het project niet. Het is goed om dit te benadrukken, er is een verwachting vanuit Nederland dat alle energie gerelateerde projecten die doorgaan dat die veilig zijn. Je kunt een hele industrie de nek omdraaien als je in de vroege pilot fase fouten maakt.
4. *Governance: Ownersip; industry standards & gas quality standards.*
   Quality is belangrijk, verschillende productiemethoden zorgen voor verschillende kwaliteit waterstof gas. Dit moet geregeld worden, omdat klanten bepaalde eisen hebben. Als de kwaliteit regulatie niet streng genoeg is verlies je bepaalde klanten. Als de waterstofgas kwaliteit eisen te streng is dan sluit je productie uit. Hier is Ad van Wijk mee bezig op Europees niveau.

5. *Organization: Principal-agent and opportunistic safeguards*.
   De wereld van de energie is al sinds mensen heugenis een geopolitieke gereguleerde aangelegenheid. Er moet wel enige mate van oversight zijn door de overheid op het gebied van leveringszekerheid, strategische reserves, kartelvorming etc.

Punt 4. Laatste opmerkingen

<u>Open vraag:</u> Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?

Nee.

8.2.7 Interview: [redacted] 24-07-2019

Punt 1. Visie waterstof als energiedrager in Nederland van interviewde

<u>Open vraag:</u> Wat is uw visie voor waterstof als energiedrager in Nederland.

Het zal een belangrijke rol spelen in de toekomstige energievoorziening. Met name in de sectoren: mobiliteit, industrie en de gebouwde omgeving. Het is belangrijk dat de transitie naar een duurzaam energiesysteem gepaard gaat met maatschappelijk acceptabele kosten. Met waterstof als energiedrager kan door middel van 'economies of scale' de kosten laag gehouden worden. Eerst zal blauwe waterstof geproduceerd en gebruikt moeten worden, als er genoeg duurzame energiebronnen zijn kan er over gestapt worden op productie en gebruik van groene waterstof. Blauwe waterstof moet gezien worden als de weg bereider voor de groene waterstof economie. Deze ontwikkeling zorgt er tevens ook voor dat de kosten maatschappelijk acceptabel blijven. Op de korte termijn kunnen we namelijk gewoon niet de benodigde emissiereductie behalen met duurzame energiebronnen en groene waterstof. Hiernaast zal de capaciteit van het elektriciteitsnetwerk moeten toenemen en nog belangrijker een waterstof transportnetwerk aangelegd moeten worden.

<u>Open vraag:</u> Wat verandert er als waterstof geïntegreerd wordt in het Nederlandse energiesysteem?

Dan heb je een stukje systeemintegratie nodig. Het is heel belangrijk om de verschillende energiesystemen die we momenteel in Nederland hebben goed verbinden en communiceren met elkaar. Het gas netwerk, het elektriciteitsnet en ook het CO2 net. Daarbij zul je dus ook faciliteiten moeten ontwikkelen waarmee je stroom om kan zetten naar waterstof. Dit zijn allemaal componenten van de energie infrastructuur die een grote rol gaan spelen. Het verbinden van deze netwerken moet ook wettelijk goed geregeld worden. In Nederland hebben we transmission system operators voor zowel gas als elektriciteit. Dit zijn TenneT en Gasunie en die goed met elkaar moeten gaan samenwerken, dit doen ze nu al bijvoorbeeld in het North Sea Power Hub. Daar komt de systeemintegratie als het project door gaat daadwerkelijk tot leven. Het idee is van de Gasunie dat ze uit de surplus van goedkope elektriciteit waterstof willen produceren. Gasunie is heel erg bezig met het verbreden met haar mandaat, ze zijn nu TSO voor gas alleen. Maar ze willen die rol ook gaan spelen voor warmte en waterstof. Het hergebruik van de oude infrastructuur is hierbij ook van belang. Hiernaast moet de in het nieuwe waterstof net ook zowel blauwe waterstof als groene waterstof door heen kunnen. Deze hebben een verschillende compositie.

Punt 2. Persoonlijke activiteiten interviewde binnen Nederlandse waterstof ontwikkelingen

<u>*Open vraag:*</u> *Met welke projecten gerelateerd aan waterstof bent u momenteel mee bezig in Nederland?*

1. H-vision
2. North Sea Wind Power Hub

Dit zijn de enige projecten omtrent waterstof waar ik mee bezig ben.

<u>*Open vraag:*</u> *Welke elementen worden er gebruikt om de businessmodellen voor deze projecten te ontwerpen/toetsen?*

Alles. Je kijkt vanuit een heel breed perspectief. We doen dit met het TECOPS-model. Technical, Economical, Commercial, Organization, Politics & Society. Dat zijn alle belangrijke componenten van een business case. Dit is ook waarop je onder anderen je risicomanagement framework optuigt. Dat is heel belangrijk. Want de vraag die je altijd zult hebben is: wat zijn de grote risico's van het project? Wat ook erg belangrijk is, is het denken in concepten en scenario's. What if?

Eén ding moet je niet vergeten zoals we nu kijken naar het H-vision businessmodel is het een 100% project. Alle interne commodity streams en cash flows van de ene naar de andere partner hebben we niet meegenomen. Dat is een overkoepelend businessmodel, maar uiteindelijk moet het businessmodel werken vanuit iedere deelnemende partner. En elke partner zal dus kijken, wie wijn mijn key partners; mijn core activities en mijn key resources. Betreft resources, dat kan zijn dat je bepaalde mensen moet hebben, dat je research en development moet uitvoeren, of dat je kapitaal nodig hebt.

Binnen deze projecten zijn voornamelijk belangrijk

- Customer Value
- Service/Product
- Technology
- Financial
- Organization
- Value exchange

<u>*Open vraag:*</u> *Welke elementen worden er gebruikt om de systeemintegratie van deze projecten in goede banen te leiden?*

Dit vind ik een moeilijke vraag. De systeemintegratie is een enorm complex en technisch onderwerp. Waar er geen eenduidige oplossing bestaat. Een vorming van een coalities is belangrijk, waarbij alle spelers en TSO's betrokken zijn. Daar zit de technische en inhoudelijke kennis. Maar wat nog belangrijker is dat er ook mensen van de TSO's aan de tafel zitten die een stukje beslissingsbevoegdheid hebben, zeker in de beginfase van zulke projecten.

Wat je ook moet doen is het opknippen van de hele waardeketen in verschillende componenten. Het moet duidelijk zijn wie welke rol kan of wil spelen in die waardeketen. De hele waardeketen moet afgedekt zijn, anders heb je in principe geen project. Binnen een coalitie moeten de spelers alle componenten kunnen afdekken. Vanaf de supply tot het eind gebruik.

- Governance: Degree of competition & unbundling; Private vs. Public ownership; Regulation of access; Industry standards
- Design perspective: System architecture & system characteristics
- Design principles: Ownership & decision rights

Punt 3. Introductie raamwerk: Comprehensive Business Modelling

<u>Open vraag:</u> De volgende elementen heeft u niet benoemd voor het toetsen/ontwikkelen van de waterstof projecten die wel worden genoemd in de literatuur. Wat is hier de reden hiervoor? Vindt u ze wel relevant?

1. Information Exchange: Absoluut belangrijk, maar hier heb je wel echt een goede projectorganisatie nodig.
2. Process alignment: Ook belangrijk, soms is de manier waarop een bedrijf zijn activiteiten organiseert en een project opwerkt/phaseert anders dan dat van zijn partners. Alle partners moet je op één lijn zien te krijgen. Dit kun je doen door middel van een haalbaarheidsstudie te doen. Een goed definitie van alle phases van een project, en decision gates moet je van tevoren al hebben afgehandeld.
3. Formal institutions: Consistent beleid op de lange termijn is ontzettend belangrijk. Daar ontbreekt het nog wel eens aan. Een "zwalkende overheid de dooddoener van business".
4. Design principles: Er is een trading hub nodig. Een plek waar vraag en aanbod van waterstof op elkaar wordt afgestemd. Die heb je momenteel voor gas en elektriciteit.
5. Control mechanisms: Riskmanagement framework moet je gewoon optuigen. Langs het TECOPS-model. Hoe manifisteert een risico zich en wat is het effect van zo'n risico op het project. Voor iedere fase zijn er risico's en je moet laten zien tot op welke hoogte je deze risico's onder controle hebt.
6. Organization: Goede gedefinieerde commerciële contracten zullen nodig zijn tussen alle spelers anders gaan de projecten omtrent waterstof niet door. In de concept select fase zal dat met name neerkomen op de head of terms. Binnen H-vision bijvoorbeeld: Shell levert bijvoorbeeld refinery gas aan de reformer die gerund wordt door van Air liquide. Dan moet er een Heads of terms komen die bepaald onder welke voorwaarden/kosten Shell haar refinery fuel gas levert aan Air liquide. Maar dit geldt ook voor de andere feedstock stromen.

Punt 4. Laatste opmerkingen

<u>Open vraag:</u> Heeft u nog laatste opmerkingen of inzichten betreffende de integratie van waterstof in Nederland die u nog wil delen?

Het is nog maar de vraag of de huidige 16 partners gaan meedoen in de volgende fase. Iedereen zit een beetje op het vinkentouw. Op basis van de feasibility studie moet er geld bij, de NPV is negatief. Ik denk dat de private partijen enkel en alleen bereid zijn om hieraan mee te werken als ook de overheid hier zich aan koppelt. Door ook mee te doen aan de volgende fase, middels een bijdrage aan het budget voor het project. De overheid kan met beleid aangeven dat iets moet maar als het niet

8.3 Appendix 3

DISTRIBUTION SYSTEM OPERATORS

GAS TRANSMISSION NETWORK

Schematic view of the main gas transport network operated by Gasunie (adapted from Gasunie, 2018)

8.4 APPENDIX 4

Variable	Unit	Low	Reference	High	Category
Uniper Maasvlakte power plant	MW	250	805	805	Power
Engie Maasvlakte power plant	MW	250	805	805	Power
Pergen Steam and power - NG	MW	143	286	571	Refineries
BP refinery RFG	MW	250	520	520	Refineries
BP refinery NG	MW	40	40	40	Refineries
Pernis refinery RFG	MW	250	650	650	Refineries
Pernis refinery NG	MW	50	100	100	Refineries
Exxon + Gunvor refineries RFG	MW			600	Refineries
Additional users NG	MW			500	Refineries

Description	Unit	Low	Reference	High
Capacity	MW output	900	2500	4000
Variable O&M dependent on MWh produced	€/MWh	0	0	0
Hydrogen output efficiency		78%	78%	78%
Investment costs	M€	592	1150	1990
Variable O&M dependent on operating hours	€ / MWh	-	-	-
Required electricity	MWh_e/MWh_output	0,08	0,08	0,08
Capture rate		0,88	0,88	0,88
Emission factor RFG	ton/MWh	0,23	0,23	0,23
Emission factor NG	ton/MWh	0,21	0,21	0,21
Fixed O&M costs	M€/year	19	37	65
RFG + NG input	MW input	1.109	3.080	4.928
RFG input	MW input	500	1.170	1.830
NG input	MW input	609	1.910	3.098
Costs for NG line	€/MWh	0,3	0,3	0,3

8.5 Appendix 5

INPUT PARAMETERS IN THE MODEL

	Parameters	Units	Min	Med	Max
General					
	Operating costs (tariffs) for CO2 storage	€/tonne	15	15	15
	Operating costs (tariffs) for CO2 transport	€/tonne	15	15	15
	[Phasing] Full H2 production in	year	2026	2026	2026
	[Phasing] Number of construction years	years	3	3	3
	[Phasing] Slow ramp-up minimum	[%]	1	1	1
	[Phasing] Slow ramp-up years	years	0	0	0
	[Phasing] FID	year	2022	2022	2022
	Power Plant Operating hours with hydrogen	hours	5,000	5,000	5,000
	CAPEX scaling factor - Economical World	[%]	150%	150%	150%
	CAPEX scaling factor - As Usual	[%]	100%	100%	100%
	CAPEX scaling factor - Sustainable World	[%]	75%	75%	75%
	Efficiency CCGT Power plant		56%	56%	56%
Technical					
	Hydrogen Demand	MW	1,183	3,206	5,276
	Natural reformer Capacity	MW output	1,081	2,915	3,888
	Hydrogen output energy efficiency		78%	78%	78%
	Required electricity	MWh_e/MWh_output	8%	8%	8%
	Capture rate		88%	88%	88%
	Unmitigated Emission factor RFG	tonne/MWh	0.23	0.23	0.23
	Unmitigated Emission factor NG	tonne/MWh	0.21	0.21	0.21
	RFG input	MW input	500	1.170	1.830
	Capital Retrofitting costs Power plant A	M€	-	162.5	192.5
	Capital Retrofitting costs Power plant B	M€	55	162.5	192.5
	Generic O&M Costs Power Plant A	€/MWh	-	2.40	2.40
	Generic O&M Costs Power Plant B	€/MWh	-	2.40	2.40
	Capital Retrofitting costs Refineries	M€	101.6	214.3	389.3
	Capital Investment costs Reformer	M€	684	1,645	1,994
	Fixed O&M costs Reformer	M€/year	22	53	65
	Costs for NG line to Reformer	€/MWh	0.30	0.30	0.30
	Capital costs H2 transport	M€	28.3	49.8	72.7
	OPEX costs H2 transport	%	1%	1%	1%
	OPEX costs H2 transport	k€/year	283	498	727
	Capital costs H2 storage	M€	-	-	190
	Operating costs H2 storage	M€/year	-	-	7
	Working gas capacity	MWh	-	-	390,000

	Parameters	Units	Min	Med	Max
	Additional transport costs for connection to backbone	M€/year	-	-	1.979
	Emission factor CCGT for comparison	tonne/MWh_e	0.38	0.38	0.38
Finance					
	Default WACC	[%]	3%	3%	3%
	Max CAPEX subsidy	[%]	30%	30%	30%
	Number of years OPEX subsidy	years	15	15	15