Exploring transition pathways for the development of a hydrogen pipeline network as key link in the future hydrogen value chain

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Preface

Dear reader,

In front of you lies my thesis, which is part of the fulfilment of the Master program Complex Systems Engineering and Management at the Technical University of Delft. Mid-April, I started off this project with the desire to make a contribution to the research field of hydrogen and to show my ability to manage individually a significantly large project, such as a masters thesis. Now, at the end of this period, I can admit that, due to the COVID-19 pandemic, these two elements took in some ways an unexpected turn. At several moments, working from home, without the ability to meet people, was a tough element that I had not expected to play such a role. However, this incentivized me even more to show my ability to self-manage this project. Thanks to the people that stood by me, during both private and study issues, I think I was able to do so.

At the start of the research, my knowledge in the field of hydrogen was very limited. However, by consulting experts, actors, teachers and other inspiring people, my level of knowledge improved step-by-step until, finally, these helpful people enabled me to fully understand the problems faced in the hydrogen transition. This was an extremely interesting, fun, informative, sometimes hard, but also valuable process. By being blessed with the possibility to talk to all actors throughout the entire system, I was given the chance to gain very interesting insights in the field of research. This all, would not have been possible without the impressive willingness of all the people I have talked to, to help me and provide me with positive support and interesting perspectives. Therefore, I would like to thank a few people.

First of all, I would like to thank my graduation committee, Zofia, Rolf and Hanxin for their constructive feedback, time during the summer and positive note when needed. Without your critical, but honest and valuable support, I would not have been able to bring this all to a good end. Although all meetings, from begin to end were online, I really enjoyed working with you and I admire your experience and knowledge on this topic and on working on projects like this.

Furthermore, I would like to thank all the interviewees that helped me by providing me interesting new perspectives, innovative ideas and knowledge. I was very positively surprised by the time you reserved for me and your intriguing stories about your experiences in the field.

Lastly, I would like to thank my friends and family for all their support and the distraction they offered me when I needed it most.

The hydrogen transition, as part of the wider energy transition, will inevitably move forward toward its goal to decarbonize the world we live in and, thereby, contributing to solutions for the climate crisis we face. Hopefully, the findings of this performed research provide, not only a conclusion for my studies in Delft, but also a contribution to the transition that the energy system is about to fulfil.

I hope you all enjoy reading!

Executive summary

The hydrogen system currently operated in the Industrial Cluster of Rotterdam, is restricted to hydrogen being produced as by-product in industrial (petro-)chemical processes. Therefore, the design of a new hydrogen value chain is required. The complexity in the design of a complete value chain is experienced in the fact that production, transportation and demand are to be developed at once, and experience high-level interdependency on various aspects. Performed research majorly focused on techno-economic supply chain optimization under demand uncertainty, thereby determining the impact of volumes on the most efficient network infrastructure and supply chain outlook. In contrast, this research, places the network infrastructure in a central role, resulting in the following research question:

Taking into account multi-actor complexity, what are viable transition pathways for the development of a pipeline network as part of the future hydrogen value chain in the Industrial Cluster Rotterdam in 2050, and what are lessons learned for other regions in the Netherlands?

To answer this research question, a methodological framework for low-carbon energy scenarios is adopted combining trend-based, actor-based and technical feasibility approaches in an iterative manner. First, a general systems analysis is performed on the existing and future expected hydrogen system. Based on the expected systems outlook, key actors are identified. A comprehensive actor analysis, by semi-structured interviews, determined actor perspectives on the development of trends/visions and value chain technologies. Analysis of the actor perceptions enabled the research to construct three possible end-visions.

The transition to any sustainable energy system should incorporate challenges and barriers, in this research included as transition issues. Lastly, the gathered data on issues and on actor perspectives for visions and value chain technologies substantiated the construction of three diverging transition pathways that are exploring possible routes towards the end-visions. Analysis of expected pipeline network activities in the pathways, led to the determination of key aspects of the pipeline network that cause lock-in effects in the development of the hydrogen value chain, which are short-term actions that have long-term impact in the transition.

The systems perspective resulted in three possible end-visions for 2050 and related transition pathways investigating the role of the pipeline network by facilitating the flow, instead of the sectoral demand focus of traditional research. The end-visions and pathways captured the aspects and complexities concluded upon during the performed interviews and extensive actor analysis, i.e. role of hydrogen in the system, the deployment of the green hydrogen, blue hydrogen cycle or both cycles, the international focus and the complexity of multiple demand sectors with varying purity requirements.

- H_2 – High purity pathway

The high-purity end-vision is dominated by the green hydrogen cycle. This system exhibits

the least complex structure since all demand sectors can utilize the same hydrogen purity, and conversion steps and utilization of PSA are minimized. Downside of this situation is that high-purity hydrogen is utilized in end-use facilities where low-purity hydrogen would suffice. Hydrogen is mostly utilized as chemical product, serving the industrial feedstock and mobility sector, and as flexibility mechanism for the electricity system. Not focusing on the possible role of hydrogen as replacement of natural gas, increases the dependency on alternatives. The national character of this end-vision minimizes the economic benefits of the Netherlands as transit country. The inability of benefiting from the economies of scale at the international market also limits the development of hydrogen volumes on a national scale. The Netherlands is not expected to be able to realize full upscaling in a nationally oriented market. The national focus causes a relatively late development of international network connections. The early focus on green hydrogen limits the upscaling of required volumes and inclusion of other markets. The restriction in development of volumes and inclusion of the built environment, limits the pipeline network to the construction of dedicated pipelines in the industrial sector connected by the regional and national backbone. However, no widespread public network is developed. The late development of international connections limits the role of the PoR.

- H_2 – Low purity pathway

The second end-vision maintains a strong role for the blue hydrogen cycle. The hydrogen flow is mainly allocated to the industrial heat and built environment sectors, meaning that hydrogen serves predominantly as replacement for natural gas. The formulation of the role of hydrogen in the system, causes a less stringent necessity for electrification of heating processes, and increases the direct application of hydrogen and electricity in end-use appliances. Therefore, the demand in the power sector and the supply of excess electricity from the grid is lower than in the first end-vision. The flow in the system gained in complexity since the system operates three hydrogen cycles, i.e. green, blue and import. The Dutch hydrogen system in this end-vision acquired a more international focus. This resulted in a larger volume flow, especially when the throughput flow of the Netherlands as transit country is also incorporated. The international import flow did not yet facilitate the phase out of blue hydrogen, which can be caused by multiple factors such as inadequate policy or not yet depreciated facilities. The pathway explores a quick upscaling of volumes by the deployment of blue hydrogen. Although volumes increase, the development of green hydrogen volumes delays due to less investment. The competitiveness of blue hydrogen and investments in infrastructure for CCS decreases the need to connect to the international market and restricts the transit role of the PoR. As volumes increase, the dedicated industrial pipelines constructed in the early phase of the transition are connected to the public pipeline network supplying the built environment. This network enables the reuse of existing natural gas pipelines.

- H_2 – Mixed purity pathway

The third end-vision is the most complex system since it represents the most diversity in origin and destination of the volume flow in the value chain and, thus, a deeply rooted combination of three hydrogen cycles. The strong international character of this end-vision incentivized the technological development, implementation of hydrogen appliances and, thus, the upscaling of volumes. However, the extent of the demand volumes require the blue hydrogen cycle to be still operational in 2050 and determines the Netherlands to be dependent on energy import, for both hydrogen and natural gas. It is questionnable whether this situation is desired. The pathway explores the most pace in the early phase of the transition by starting-off with a low-purity standard to benefit from the large volumes in the heat industry and utilize blue hydrogen as upscaling mechanism. This pathway accepts the utilization of green hydrogen as source for heat in the early phases at the expense of the loss of high-purity hydrogen. The major interconnections to the international market enable the required cost reductions for green hydrogen technologies and realize the phase out of blue hydrogen as import volumes increase, which results in the shift in system standard to high purity. The pipeline network evolved to facilitate the significant pace in upscaling of volumes and high interconnectivity to the international market. The uncertainty in this pathway is caused by the dependency on the international market.

The analyses performed in this research enabled the interpretation of major challenges in the development of the hydrogen value chain. The future actor regime defines problem perceptions related to the public vs private network, the sensitivity regarding public interference and control, the competition between sectors and the required high-level actor cooperation. Furthermore, the extensive power of industry being observed throughout all analyses follows from the identification of several factors, such as the strong urgency to decarbonize, sufficient investment power, the high expected volumes over a manageable number of actors with production and consumption centralized in a few clusters, and the fact that industrial actors control processes over the full width of the value chain. The public network operator should facilitate the inclusion of other sectors in the transition, but has a significant stake in the transition, due to the existing pipeline network infrastructure and the elimination of natural gas as energy carrier in the coming decades. The network operator and industry have opposing interests as entering versus existing system actors, but exhibit both the power and position to steer the transition. Therefore, political guidance is required to enable all sectors to benefit. From a technical point of view, the transition pathways let observe that the major challenge is to operate three hydrogen cycles, i.e. green, blue and import, in one value chain. The efficient combination of multiple production flows towards different demand sectors with varying purity requirements in one pipeline network, results in a complexity that is extensively described by this research, but which should be practically dealt with in the coming decade.

It can be generally concluded that the type of pipeline preferred, majorly depends on the availability of existing natural gas pipelines. This availability depends among other things on the location of the pipelines, the location of supply and demand flow, and on the development of hydrogen volumes and the general function of hydrogen in the system that affect the remaining demand for natural gas. If the determined factors show negative consequences for availability of existing pipelines, new dedicated pipelines are constructed. Physical blending is not considered as feasible alternative by the system actors.

Evaluating the role of the pipeline network in the development of the hydrogen value chain enabled the identification of five generalised key aspects: the type of pipeline, network ownership and operation, network strategy in the transition phase, the role of the network operator and industrial sector, and the pipeline capacity and outreach. These aspects are the main cause for lock-in effects, meaning that they influence the long-term impact in the transition of the value chain with respect to: the extent of market expansion, the security of supply, sufficient pace of upscaling of volumes, energetic and economic efficiency of the system, and the level of fair competition.

The qualitative approach and used methods during the research, in combination with time constraints and scope, enforced the adoption of assumptions and simplifications, leading to several limitations. The research framework opts for the analysis of the impact of actors' decisions and perspectives on the visions and on the technical outlook of the value chain. However, the full methodological dynamics describe also affection of the actor network by visions and value chain. Since this direction of influence is not assessed, the impact of policies or other political mechanisms is not deliberately investigated. Furthermore, the modelling of the end-visions showed a shortcoming in the ability to determine import and export flows. Therefore, more extensive modelling is required to gain deeper understanding of the role of the PoR as international hydrogen hub.

Lastly, the validation of the pathways with the actors is not performed due to time constraints. This is the first element to be fulfilled if the research is continued. A relevant next step would be to determine the detailed technical and economic impact of the transition pathways by advanced modelling or simulation.

Abbreviations

ATR	Autothermal reforming
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CC(U)S	Carbon capture utilization and storage
CO_2	Carbon dioxide
DSO	Distribution system operator
EB	Dutch energy tax
ETS	Emission trading system of EU
H_2	Hydrogen
ICR	Industrial Cluster of Rotterdam, meaning the industrial area around the port including the directly connected built environment
NG	Natural gas
ODE	Sustainable energy surcharge
PoR	Port of Rotterdam, just the port area with the Port of Rotterdam authority as owner
PEM	Proton exchange membrane
PSA	Pressure swing adsorption
RED	Renewable energy directive
RES	Renewable energy sources
SDE++	'Stimulering Duurzame Energietransitie'; a Dutch subsidy mechanism
SMR	Steam methane reforming
TSO	Transmission system operator

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Chapter 1

Introduction

1.1 Research background

Following the targets set in the Paris Agreement and, more recently, the announcements made in the European Green Deal, the global energy system has to undergo a significant transformation. The global energy demand is expected to escalate in the coming decades, while at the same time there is a growing consensus that managing GHG emissions is crucial to prevent far stretching consequences for the climate system (Abdalla et al., 2018). Low-carbon electricity provided by renewable energy sources may become the most preferred energy carrier. However, the intermittency of these energy sources increases the complexity in balancing supply and demand. Furthermore, particular sectors, such as industry and heavy-weight mobility, experience difficulty in the electrification of processes due to their reliance on high-grade heat or fossil fuels, often to be supplied by molecules (Møller, Jensen, Akiba, & Li, 2017). Electricity is also not the most preferred energy carrier to transport over longer distances (Wulf & Zapp, 2018).

1.1.1 The hydrogen transition

Hydrogen could be the missing link for multi-purposes in this energy transition and is extensively included in all political strategies. It can be used for balancing of the (international) market due to its suitability for long-distance transport and seasonal energy storage, as syngas blended with CO2, as high-grade heat, in fuel cells and as feedstock (Andrews & Shabani, 2012; Blanco & Faaij, 2018). Its widespread variety in characteristics and potential applications, makes it a promising technique throughout the entire chain and explains the increasing focus on the development of the hydrogen economy. As it is described now in future strategies, the hydrogen value chain is about to expect significant expansion and innovation. The combined utilization of hydrogen and electricity can provide the backbone of the future (Ball & Weeda, 2015).

The concept of the transition towards this hydrogen economy, which should be co-evolved with electrification, can be found back up to the late 70s, but faced increasing interest throughout the 2000s (Crabtree, Dresselhaus, & Buchanan, 2004; Dickson, Ryan, & Smulyan, 1977; Moliner, Lázaro, & Suelves, 2016). The hydrogen transition faces significant deviations between the intended direction and the current outlook due to unexpected events (*figure 1*). This difference is observable in the view, presented a decade ago, that determined no sense to speed up the role of hydrogen up to 2030, a low contribution up to 2040 and a forced market introduction of hydrogen after 2040 (Hennicke & Fischedick, 2006). This vision is nowadays hardly imaginable but could be reconciled with the descending slope at that time in the graph in *figure 1*.

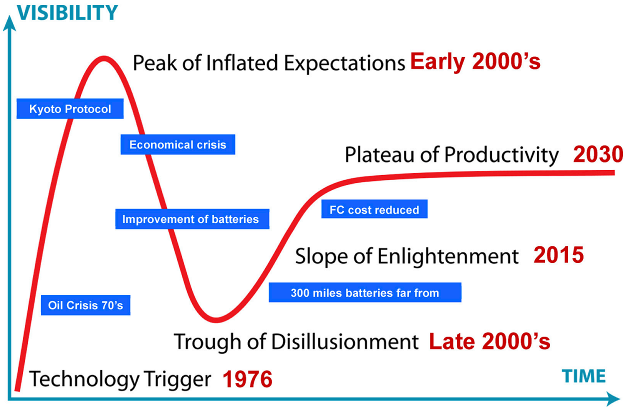

Figure 1: *The hype cycle for the evolution of visibility of the hydrogen economy versus time (Moliner, Lázaro, & Suelves, 2016).*

1.1.2 The hydrogen value chain

The widespread utilization of hydrogen in the energy transition faces challenges on the level of production, infrastructure, sustainable resources, end-use technologies and regulations (IEA, 2019b). Therefore, to let the future hydrogen-based economy deal with these challenges, the design and assessment of a viable hydrogen value chain is required. This value chain should be designed from production to storage to conversion to transport to end-use (Chen, Kumar, Wong, Chiu, & Wang, 2019).

The development of the value chain components is in its early stages and the transition period taken into account in strategy reports is at least towards 2050. Therefore, the transition is in its take-off phase and all value chain elements are still to be developed on core aspects as efficiency and scale to acquire mature technologies at competitive cost-prices (European Commission, 2020). However, from a systems perspective, the interconnection between the value chain components is key and is to be considered from the earliest systems design phases on (Bento, 2008). The complexity in the hydrogen value chain arises from the fact that most elements do no not exist yet and need to be developed simultaneously (Noordelijk Innovation Board, 2017). This simultaneous development typically shows multiple chicken-egg problems in the triangular relationship between supply, demand and infrastructure. Investments in production facilities are only made when demand is guaranteed and interconnection with the demand centres is facilitated, and vice versa.

Besides the interconnection of the elements within the hydrogen value chain, the integration of the value chain into existing energetic and chemicals sectors should be assessed in the coming years (Quarton & Samsatli, 2020).

1.1.3 The hydrogen network infrastructure

In the value chain, the network infrastructure is the essential link between supply and demand. Various transportation means do exist for hydrogen, i.e. tube trailers, ships or pipelines. What alternative is preferred depends on the context; the application of hydrogen and to whether the state of hydrogen is gaseous, liquid or attached to other molecules (Abdalla et al., 2018). It is clear that for upscaling of demand and production volumes, the construction of a large scale hydrogen pipeline infrastructure is required (Smit, Weeda, & De Groot, 2007). Where intercontinental transport is likely to go over sea, transport by pipeline would be the cheapest alternative for the transportation of hydrogen on a national and European level (Ministry of Economic Affairs and Climate Policy, 2020a).

The European Green Deal explicitly recalls that it should foster the deployment of innovative technologies and infrastructures, such as hydrogen networks, and that some existing infrastructures will require upgrading to remain fit for purpose and climate resilient (European Commission, 2019). Although some parts of the existing natural gas grid are suitable or can be adjusted to facilitate the transportation of hydrogen, major investments are needed to enable a future hydrogen pipeline infrastructure. In a liberalised market, low-profile governance is often preferred, but, in this case, it may fail the transition since the infrastructure is a common good and a dominant element in the value chain that requires political guidance (Bleischwitz & Bader, 2010; Hisschemöller, Bode, & Van de Kerkhof, 2006).

The development of a hydrogen pipeline infrastructure is gaining complexity on a multi-actor level since the energy system consists of various types of consumers, TSOs, DSOs, traders, producers and is regulated by the government. The multi-actor decision-making process and the interdependency between demand and supply development in the future hydrogen value chain increases complexity further. The role of the government is critical, but uncertain, since the energy transition could require more involvement or a more active role of specific public actors. Even the best technologies may fail if the required socio-economic conditions are not in place, which are to be largely shaped by government policies (Berkhout, Smith, & Stirling, 2004; Hisschemöller et al., 2006).

1.1.4 Necessity for the Netherlands

Since the exploration of the Groningen gas fields in the early 1960s, the Netherlands played a significant role in the natural gas system. The enormous revenues that the state collected, permitted the growth and maintenance of the Dutch welfare state (Correlje & Verbong, 2004). The revenues reached a total of over 400 billion euros over the period of 1965 until 2018 (CBS, 2019a). To maintain their prominent role in the European gas system and their level of welfare, the Netherlands could be, and should be, in the position of pioneers in rolling out the hydrogen network. Because of its strategic location for the international infrastructure, Rotterdam draws the attention as potential hydrogen hub and transit port for the Netherlands and north-west Europe (Port of Rotterdam, 2020b).

1.2 Problem statement

The research background introduces problem perceptions in the hydrogen transition, related to the development of the hydrogen value chain and the role of the pipeline network infrastructure in this chain; visualised in *figure 2*. From the sections above, two general problem perceptions can be identified; the techno-economic complexity regarding the feasibility of the utilization of hydrogen technologies, and the socio-technical complexity in the start-off phase of the value chain development process. For the second aspect, increased complexity is experienced in the multi-actor decision making process and the interdependency between demand and supply development in the future hydrogen value chain. The new to be designed value chain requires far stretching cooperation between actor groups characterised by varying interests, likely to be contradicting in a liberalized market. The network infrastructure is the key link between supply and demand markets, and pipelines, in particular, are required to enable sufficient volumes and cost-effective transportation over longer distances. The multi-actor complexity in the development of the

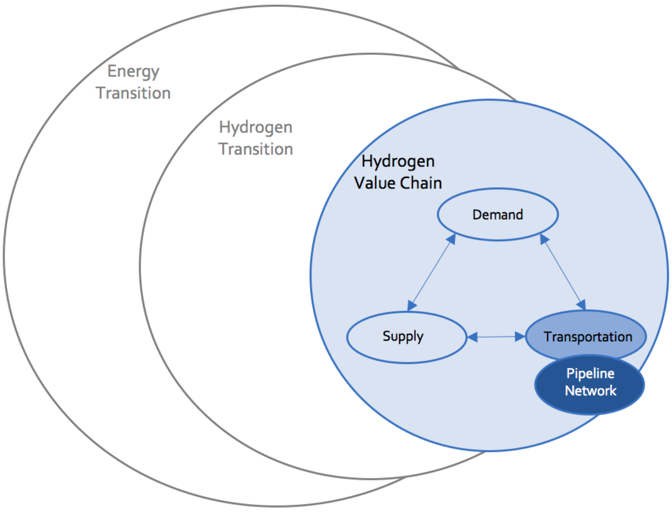

Figure 2: *Presentation of the research scoping introduced in* section 1.1, *the blue elements provide the starting point for the literature study.*

pipeline network is one of the first barriers to be overcome to enable the hydrogen transition to move forward. The choice for this problem area is further investigated in the literature study in *chapter 2*.

1.3 Research objective and research questions

The objective of this research is to contribute to the development of hydrogen transportation by pipeline, taking into account the actor complexity and the development of the future value chain. The study should include desired system components, actor responsibilities and challenges to be overcome in the transition period and end-situation. The outcomes of the project should be scalable, transferrable and oriented towards further development of the network infrastructure in a national and international context. Therefore, both strengths and limitations of the research should be addressed, as well as recommendations for similar and related projects that are to be developed in the future. This objective is concluded in the following research question, for which the scientific background is explored in the literature study in *chapter 2*.

"Taking into account multi-actor complexity, what are viable transition pathways for the development of a pipeline network as part of the future hydrogen value chain in the Industrial Cluster of Rotterdam in 2050, and what are lessons learned for other regions in the Netherlands?"

The specification for the industrial cluster of Rotterdam will be discussed in *section 1.4*. The following sub questions are formulated based on the chosen research approaches, methods and designed research framework. Aspects all further discussed in *chapter 2*.

1. What is a suitable research set-up to explore the development of a hydrogen pipeline network, as a crucial part of the development of the value chain towards 2050, that complements currently executed research?

2. What is the outlook of the current hydrogen system, in both the Netherlands and the ICR, and what are relevant future value chain elements to consider in exploring the development of the pipeline network?
3. How do the actor network dynamics influence the transition period, and what are the actor perspectives on the development of the hydrogen value chain and visions, focussing on the pipeline network?
4. What are, based on the actor perspectives, three viable end-visions for the hydrogen value chain in 2050?
5. What are general transition issues to be faced in the transition towards the hydrogen value chain in 2050 and what are the key network actors empowered to deal with them?
6. What are possible transition pathways, focussed on actions related to the pipeline network, towards the constituted end-visions for 2050 and what lock-in effects can be defined in the transition?

1.4 Research scope

1.4.1 Geographical scope

The problem described in this first chapter shows high relevance for the Netherlands. Two factors can be identified for the Netherlands to set their focus on the development of hydrogen infrastructure. The first factor is the decarbonization of the energy mix. The Netherlands exhibits, besides electricity, high dependence on natural gas because of the exploration of the Groningen gas field in Slochteren. The abundance of natural gas determined the energy system to be designed on the utilization of molecules as energy carrier. Hydrogen could be a sustainable solution to decarbonize the gas chain and to offer an affordable, clean and reliable source of supply (Ministry of Economic Affairs and Climate Policy, 2020a).

The second important factor is an economical argument. The extraction of natural gas earned the Netherlands its revenues that reached a total of over 400 billion euros over the period of 1965 until 2018 (CBS, 2019a). If this extraction is quit, this source of income will not be available anymore. Next to natural gas, the decarbonization of the energy flow will have consequences for the Netherlands as a transit country for other fossil fuels. To maintain its economic position and to reuse existing assets, such as the natural gas network, the Netherlands should adopt a new strategy; hydrogen.

To achieve its position as transit country, the Port of Rotterdam is essential as the hub for international energy flows, which it already is nowadays. Considering the expected hydrogen demand for industry in the neighbouring countries, the offshore wind potential of the North Sea and the possible hydrogen transport overseas, Rotterdam is a clear area of focus (Ministry of Economic Affairs and Climate Policy, 2020a; Port of Rotterdam, 2020b). However, the interaction between Rotterdam and surrounding areas is included in this research since the hydrogen system is not bounded by regional borders in the Netherlands. The geographical scope, thus, determines the focal point of orientation from where the national hydrogen system is explored.

1.4.2 Temporal scope

In general, energy transitions require short-term steps for long-term change (Kemp, Rotmans, & Loorbach, 2007). This is where a main challenge for transitions is originated. Low-carbon transitions typically are defined as long-term processes influenced by multi-facets (Geels, Berkhout,

& van Vuuren, 2016). A transition requires large-scale investments with high capital costs and should, therefore, be guided by long-term stable institutional governance. As of 2020, the long-term is defined as 2050. Up to 2030, most strategies are already defined, and business cases are being finalized. Looking beyond the horizon of 2030, enables the researcher to explore the uncertainties up to 2050. Therefore, the temporal scope of this research is set at 2050. The third scoping aspect, the technical scope, will be further explored and explained in the systems analysis in *chapter 3*.

1.5 Alignment of research with CoSEM program

The problem captured in the research question could be characterised as an intervention or transition in the energy system. This requires systems thinking, understanding of actor complexity and the ability to operate in the playing field of socio-technical systems. The CoSEM program adheres to this problem area since it is built upon three pillars:

- Complexity
- Systems engineering
- Management

With skills obtained for these three disciplines, interventions can be designed. The interventions are characterised by a strong relation to public interest and policy relevance.

Structuring the research by theories on transition management for the decarbonization of the energy system and supporting the analysis by multiple scientific methods, provides the scientific context. The scientific context is further described in chapter two by placing the research in the wider theoretical context. The managing of this research project of six months requires good communication, cooperation and reflection skills. These are abilities and skills that were taught and trained during the two-year master program Complex Systems Engineering and Management at the TU Delft.

1.6 Thesis outline

This thesis consists of three parts as shown in *figure 3*; the conceptual and exploratory phase, the empirical and analytical phase, and the synthesis. It starts in *chapter 2* with a theoretical and practical literature background analysis that results in the research approach and research framework. *Chapter 3* provides the analysis of the current and future hydrogen system and defines the elements of the value chain being relevant for the scope. *Chapter 4* is the actor analysis that builds forth upon the systems analysis and provides actor perspectives that provide the data input for the chapters thereafter. *Chapter 5* quantifies the actor perceptions and complements it by a narrative for three possible end-visions for 2050. *Chapter 6* concludes the transition issues, as perceived by the actors, in the transition period towards the end-visions. The issues constitute challenges and actions to be followed in the design of the transition pathways. *Chapter 7* combines all gathered information in three transition pathways towards the end-visions for 2050. Finally, *chapter 8* provides the discussion and conclusion of the research, and recommendations for further research.

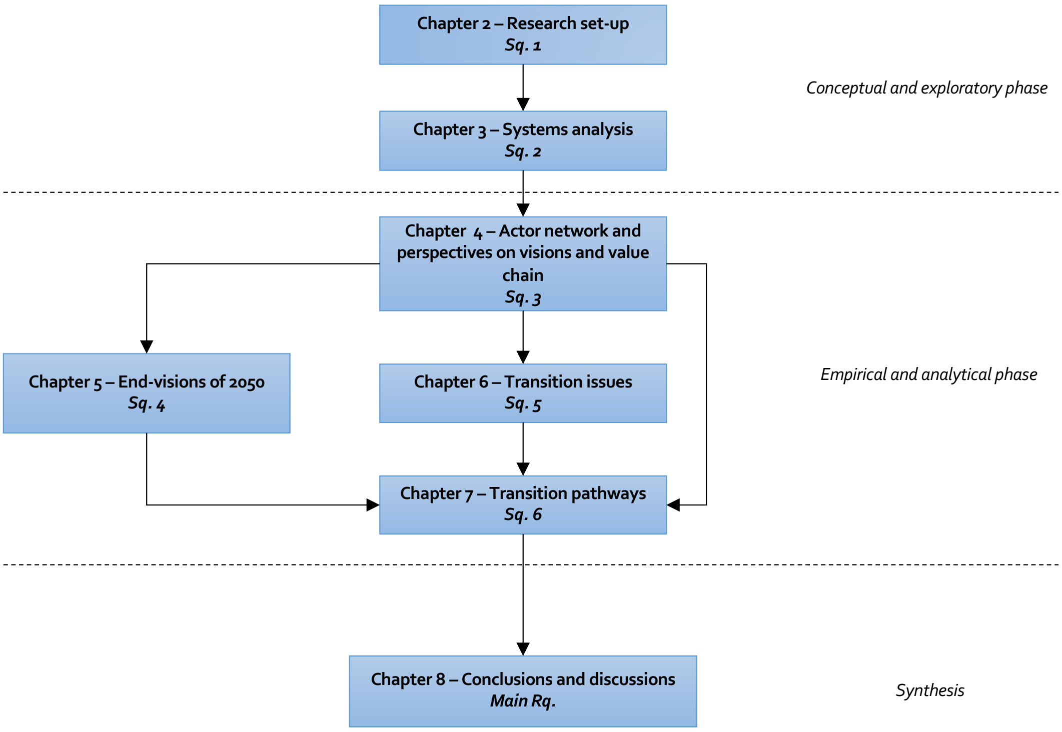

Figure 3: *The thesis outline presenting the research flow through all chapters.*

Chapter 2

Research set-up

This chapter provides the summarized literature study and, subsequently, the research framework. The literature study consists of two parts: (1) the literature study on performed researches that leads to the knowledge gap for which the research questions are composed, and (2) the theoretical background study discussing the relevant theories, correlated to the problem context of the research questions, that are required for the research approach. The theoretical background study will lead to the research framework, including methods and theoretical approaches used in the chapters thereafter. This chapter answers sub question 1:

What is a suitable research set-up to explore the development of a hydrogen pipeline network, as a crucial part of the development of the value chain towards 2050, that complements currently executed research?

2.1 Literature study for knowledge gap

The scope for the literature study follows from the problem statement in *section 1.2*. Therefore, the focus is set on research currently conducted on the hydrogen value chain and the pipeline network. More explanation on the search method, selection of aspects and the full literature table are attached in *appendix B*.

2.1.1 The hydrogen value chain

Discussing this concept, it is useful to first understand the difference between a value chain and supply chain, although both concepts have much overlap. For both aspects, many studies exist, but research on the aspects of the value chain is less expounded. The value chain is oriented from customer requirements, where the supply chain is based on product requirements. A value chain requires alignment between what a consumer wants and what is produced in the supply chain. In this perspective, the movement of resources add value in two directions, i.e. financial resources to the supply side and derived value from service to the demand side. There can be distinguished between technical, organizational, personal and market values. A supply chain is more focused on cost reduction and deriving operational efficiency, and the flow is strictly from supplier to customer. Efficient supply chains result in cost reductions (Feller, Shunk, & Callarman, 2006). Most studies in the field of the hydrogen transition focus on optimization of the supply chain.

The provided definitions of value and supply chains support the finding that the majority of these studies are optimization models focusing on techno-economic possibilities, and neglect strategic, institutional and social components. Considering the design of the hydrogen economy, a focus on the efficiency of the supply chain is very restricted. Very often, the concepts of value chain and supply chain are misused.

The studies of Almansoori and Shah, 2009; Nunes, Oliveira, Hamacher, and Almansoori, 2015; Reuß et al., 2017; Samsatli and Samsatli, 2019, are examples of optimization studies for the design and operation of 'a' hydrogen supply chain. The denotation of 'a' hydrogen supply chain is a conscious choice since these studies model the supply flow of one hydrogen product in 'the' hydrogen value chain. These studies show specific interest in the physical layout of the supply chain and the modelling of demand uncertainty. The studies of Almansoori and Shah, 2009; Samsatli and Samsatli, 2019, target only the demand in the transport sector, while Reuß et al., 2017, adopt the most systems perspective. Nunes et al., 2015, introduce the aspect that hydrogen serves as a replacement for natural gas, as heat source, and discuss specifically the injection of hydrogen in the gas grid. However, the link with other demand sectors and the impact of injection in the gas grid to other sectors for this supply chain is ignored. The study of Mueller-Langer, Tzimas, Kaltschmitt, and Peteves, 2007, differs from these studies in the fact that it is not an optimization study, but a techno-economic analysis on production techniques in the value chain. This focus on the production side causes shortcomings in discussing other elements in the chain. The same holds for the study of Breyer, Tsupari, Tikka, and Vainikka, 2015, but then specified for solely power-to-gas production.

Apart from the focus on elements within the value chain, some studies investigate the integration between hydrogen and other systems. Quarton and Samsatli, 2020, research the integration of hydrogen and CCS to decarbonize the energy system. However, their only focus is on the integration of the hydrogen system in the electricity sector to serve as flexibility mechanism. Farahani et al., 2019, specified the integration of hydrogen and electricity even further by simulating the role of FCEV's as storage and power unit. These studies show relevant insights in technical feasibility and system control, but little expose the stakeholder roles and their influence in the full system design.

2.1.2 The hydrogen pipeline network

As design alternatives in optimization studies, the transport of hydrogen by pipeline, tube trailers or boat is considered. When considering transportation by pipeline, the literature distinguishes among three alternatives:

- Dedicated hydrogen pipelines. New to be constructed pipelines for the transportation of hydrogen. This new network could be operated simultaneously with the existing natural gas network.
- Reusing existing natural gas pipelines. Some particular pipelines of the current natural gas network could be made applicable for the transportation of hydrogen.
- Hydrogen injection into natural gas pipelines. By 'blending' hydrogen into methane, a mixture is created that could be transported in the current natural gas pipelines.

The literature on these specific alternatives will be elaborated on in the sections below. However, one aspect related to hydrogen transport is studied in general; safety. The safety of hydrogen transport in pipelines is researched on the technical feasibility and associated risks. Safety has high priority regarding implementation of hydrogen technologies and is noticeable in the majority of the studies because of hydrogen's critical ignition and combustion characteristics (Najjar, 2013).

In the transportation of hydrogen by pipeline, safety issues are related to its high flammability, auto-ignition temperature and wider explosive and fire danger (Labidine Messaoudani, Rigas, Hamid, & Hassan, 2016). Jo and Ahn, 2006, were early investigators in safety management of high-pressure pipelines required to transport hydrogen over large distances. An aspect that was expanded by Witkowski, Rusin, Majkut, and Stolecka, 2017. A different perspective on safety issues is highlighted by Scott and Powells, 2020 that were able to research the domestic acceptance of hydrogen as a gas for cooking and heating. Although the safety issues are significant, they can be overcome and will not form an insuperable obstacle towards the technical feasibility of a hydrogen pipeline infrastructure.

Dedicated hydrogen pipelines

The research on dedicated hydrogen pipelines is mainly to be found as part of studies on the general lay-out of the network in the supply chain. Based on different scenarios for demand development, the studies determine what type of transport is preferred and reflect upon the associated economic conditions. Therefore, case studies are mostly performed to present the outcomes. Smit et al., 2007, determines the cost of a network infrastructure for the Netherlands and refers to the use of blending to boost hydrogen demand. The required increase in demand to make pipeline transport profitable, is emphasized by the study of Baufume et al., 2013, which determines for the German case that low demand volumes are to be supplied by tube trailers.

The structure of most studies is similar, they start with demand estimations and subsequently model what type of hydrogen production (*SMR vs electrolysis*) suits what production location (*centralised vs decentralised*), what type of transportation (*pipeline vs truck*) is feasible and what the costs are for their chosen scenario. As Tzimas, Castello, and Peteves, 2007, points out, the hydrogen network infrastructure could differ with respect to the natural gas network due to distributed power systems based on renewables, which could make the need for high pressure transmission lines futile. Tlili et al., 2020, argue that electrolysis near the source is more viable for higher penetration rates but that, in early stages, production near demand is most preferred. The high correlation between type of transport and type of production for hydrogen is emphasized by Moreno-Benito, Agnolucci, and Papageorgiou, 2017. The studies described here largely focus on the spatial and technical design of the network infrastructure related to demand development.

Where LNG is important to the natural gas infrastructure, liquified hydrogen (LH_2) could play a similar role in the transportation of hydrogen, which is investigated by Agnolucci, Akgul, McDowall, and Papageorgiou, 2013. Demand assumptions have a direct causal link to the pipeline diameter; an important cost parameter that receives attention from Andre et al., 2013; Balta-Ozkan and Baldwin, 2013; Johnson and Ogden, 2012. The majority of these papers are still considering the alternative for large scale transportation by both pipelines and trucks due to undeveloped demand. This research perspective is to be questioned, since the attention has recently expanded also to sectors such as large industry and domestic appliances and not solely on FC-vehicles as assumed by the majority of previous studies. The broader demand development decreases the demand uncertainty and enables the long-term vision to shift to a middle-term strategy, which increases the interest in pipelines. Reuß, Grube, Robinius, and Stolten, 2019, endorse the line of reasoning that higher demand levels are required, and will be met, for the viability of pipelines.

Reuse of existing natural gas pipelines

By multiple papers addressed as final stage of the transition towards a hydrogen pipeline infrastructure, is the use of the existing gas-grid for transportation of green gasses, in particular hydrogen. As Haeseldonckx and D'haeseleer, 2007, implicate, starting with hydrogen injection is a suitable intermediate step since the full utilization of the gas grid for hydrogen requires cooperation on a European level since many countries serve as transit countries in the natural gas system. Following, according to Dodds and Demoullin, 2013, the decision to convert the system depends on economic factors, performance of technologies and willingness of governments to organise this conversion program. Even if these aspects turn in favour of conversion, Ma and Spataru, 2015, describe the hurdle to be overcome, which is that the national transmission grid is not suitable for hydrogen and that a new high-pressure pipeline system should be built. B. Wang et al., 2018, conclude from the economic perspective that expansion and reformation of the existing system simultaneously will give best results. On the other hand, Hickey, Deane, McInerney, and Gallachóir, 2019; Speirs et al., 2018, are more reserved regarding conversion to hydrogen. The study of Speirs includes various gasses, next to hydrogen, in his research and does not find a clear best option for decarbonisation of the gas-grid. Hickey, on his turn, describes the expected shortfall in demand for gas use beyond 2030 due to the electrification of processes. This may lead to potential disconnections in the distribution network and provides a less optimistic future for the expensive conversion of the gas-grid.

Hydrogen injection into natural gas pipelines

This alternative is the least costly and easiest to accomplish in the near future. de Vries, Mokhov, and Levinsky, 2017, conclude that the maximum hydrogen addition that can be injected without required adjustments depends on the composition of the natural gas but is roughly up to 10%, which is also taken as upper constraint by Pellegrino, Lanzini, and Leone, 2017. However, as Hafsi, Elaoud, Akrout, and Hadj-Taïeb, 2017, the composition of natural gas comes with an uncertainty for presence of other components than hydrogen and methane. The upper hydrogen injection constraint is determined by multiple studies, but the values found differ somehow a little, i.e. Kuczyński, Łaciak, Olijnyk, Szurlej, and Włodek, 2019, aim for a limit up to 15-20%, which is more in line also with the value of 15% found by Witkowski, Rusin, Majkut, and Stolecka, 2018. Other papers, such as Gondal, 2019; Timmerberg and Kaltschmitt, 2019, present more comprehensive conclusions and distinguish between compressors, pipelines, end-use appliances for determining injection limits and find that, with adjustments in the system, shares up to 50% are feasible. Timmerberg and Kaltschmitt, 2019 dive deeper into the discussion of the pipeline infrastructure and conclude that the most economical alternative would be to transport hydrogen in the existing natural gas system. However, this will be unrealistic in the near future.

2.1.3 Knowledge gap

In general, the majority of studies focus on the design of the hydrogen supply chain from a techno-economic perspective. The applied techno-economic optimization models optimize the economic efficiency of the supply chain under demand uncertainty, hereby providing case-specific results regarding the preferred lay-out of the supply chain. As indicated, the supply chain focus is inherently related to the optimization of a singular product flow, which is to be observed in literature by the sectoral approach of the research studies, aiming for a specific demand sector. This approach fails to provide a sufficiently adequate investigation of the multi-applicability of hydrogen as a product, which can fulfil demands in various sectors. The hydrogen cycle transported by pipelines has a convergent start, multiple flows from different production methods to one flow through the pipeline network infrastructure. Subsequently, this flow is diverging again to the various demand sectors with hydrogen as different types of products. Considering this full cycle complexity is critical in the design of the future hydrogen system and is dramatically simplified in the supply chain optimization studies. Assessment models have high relevance in low-carbon transitions, but simplify societal dynamics and aspects of transitions, therefore the socio-technical transition analysis should complement these (Geels et al., 2016).

A value chain perspective is required that approaches the full systems complexity with an institutional, social and strategic focus while taking the techno-economic specifications into account, as explained in *section 2.1.1*. The value chain approach with a full systems perspective lends dignity to the socio-technical problems addressed in the problem statement in *section 1.2*.

The argument of the restricted view of techno-economic optimization studies also applies to the studies on hydrogen pipeline transport, included in the second part of this literature study for the knowledge gap. The high case-specificity of the optimization studies restricts the generalizability of the acquired quantified results on pipeline alternatives. Furthermore, the demand assumptions made in the studies are often outdated due to the increasing interest in the hydrogen transition of the past few years. The more recent studies do indicate that for the expected volumetric flows, the adoption of a pipeline network infrastructure in the hydrogen system is inevitable.

The studies on the pipeline transportation let observe that blending, new dedicated pipelines and the reuse of the existing network are feasible alternatives in both technological and economic sense. This implicates that it now depends on socio-technical factors what alternative is preferred. The socio-technical factors could adhere to, among other things, actor dynamics, strategies and behaviour or institutional aspects. However, the current research does not provide conclusions on the applicability of the pipeline alternatives in the wider context of the hydrogen system and no studies include all three alternatives in one assessment. Therefore, an investigation is required showing on what factors the development of the pipeline network depends in the context of the development of the value chain, as argued upon in the paragraph above.

The future hydrogen chain is to be designed, financed, constructed and operated by the system actors. Therefore, it is crucial to focus on their perspectives and requirements so that a system can be created where, throughout the full chain, the most value can be added. Hydrogen as a product can be utilized in many sectors and in many different forms, which results in different cycles that should be designed interdependently. However, to do so, a full systems perspective is required focusing on the three building blocks of the chain: supply, demand and network infrastructure. Current research either explores the utilization of hydrogen as fuel or the utilization of hydrogen as natural gas. All roles of hydrogen should be combined in one study to determine system impacts.

By combining the socio-technical perspective with the perspective of the value chain, this research provides a type of analysis that is innovative and relevant. A socio-technical transition is typically a complex and long-term multi-actor problem case (Geels, 2011). Therefore, to distinguish between short-term actions and long-term impacts, the timeline of analysis should be accordingly. The aspects discussed here provided the ingredients for the main research question in *section 1.3*.

2.2 Literature study for research framework

This section investigates the theoretical fundament that enables the approach towards the answering of the main research question. Following the main research question, the general research framework should be based on a long-term oriented socio-technical transition approach with a key role for the actor network.

2.2.1 The actor network in socio-technical systems

Transitions in socio-technical systems often require deep fundamental changes in the structure of a system. These changes can relate to technology, governance and institutions, market, consumer dynamics, infrastructure, culture and scientific knowledge, and are all characterised by a high level of actor involvement (Geels, 2011). Energy systems are often referred to as socio-technical systems since they facilitate production and demand of goods or services to be connected, with a crucial social function of the network infrastructure. Social aspects can relate to standards in the system, but also to regulation and policies that define the contours and norms of the system (Chappin, 2011).

The importance of the actor network in the transition process is described by the multi-level concept (Geels, 2002). This concept decomposes the transition process in three levels to understand the full picture; socio-technical landscape, socio-technical regime and niche level. It is argued that changes in the regime level (the 'set of rules' shared by actor groups) enable permanent change of the landscape level (the energy system that is deeply nested in the society in the Netherlands) (Geels, 2011). The regimes of these actor groups are the 'deep structure' of a socio-technical system and are responsible for the system elements and their production (Geels, 2004). The transition in the regime level develops markets, institutions and industries when the developments and practices in the niche level become accepted on a more regular base throughout the system (Berkhout et al., 2004; Eames & McDowall, 2006). Since this acceptance is currently experienced, following various reports, such as the Green Deal (European Commission, 2019), the actor network is determined to be key in the next transition steps and in this research.

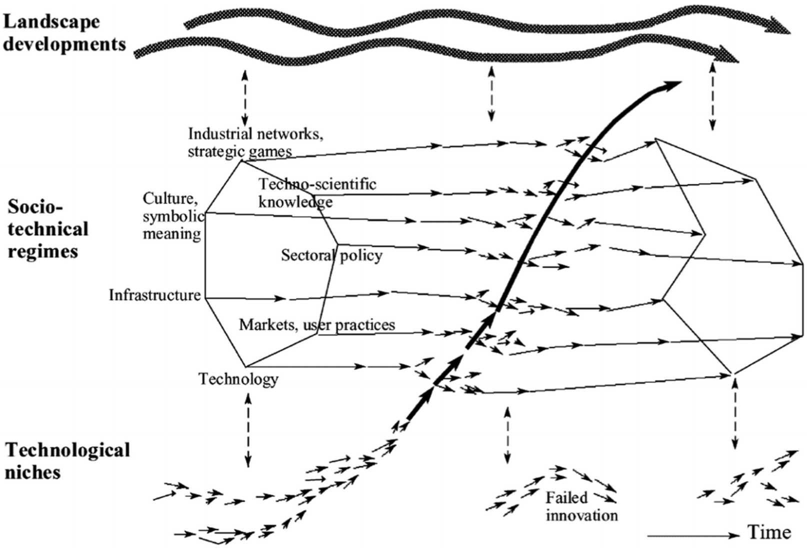

Figure 4: *The multi-level perspective (Geels, 2002).*

2.2.2 Long-term vision exploration in socio-technical transitions

To describe possible future impacts, typically, scenarios are deployed. The future impacts are caused by decisions made by systems actors (Höjer et al., 2008). There are various ways to describe impacts and, therefore, scenarios can be present in many different categories. In literature, three main categories are defined: predictive, explorative and normative scenarios Börjeson, Höjer, Dreborg, Ekvall, and Finnveden, 2006. These are related to the questions: *What will happen?*, *What can happen?* and *How can a specific target be reached?*.

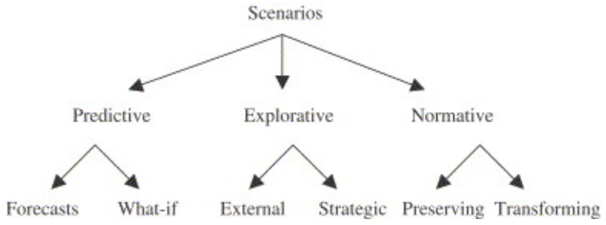

Figure 5: *Scenario framework (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006).*

The hydrogen transition itself could be appointed a specific target, or multiple specific targets, one of which is the full deployment of hydrogen as an energy carrier in a decarbonized energy system. Therefore, scenarios for the hydrogen transition could be referred to as normative. When the development of a pipeline network in the hydrogen value chain is considered, there are specific targets as well. The difference is that these specific targets are varying among all actor's perspectives. The actors have a clear vision for their own desired system, but from a systems perspective, the desired final situation is not specific, meaning that the explorative scenario could also apply. Explorative scenarios are applicable to studies where the framework is required for development of policies and strategies (Svenfelt, Engström, & Höjer, 2010). They provide support if the research aim is to explore system developments on the long-term that are likely to occur from a variety of perspectives (Börjeson et al., 2006). This variety refers to the systems perspective that accounts for the full range of actor perspectives.

In the explorative scenario, there is a distinction between external and strategic scenarios. External scenarios orientate on elements beyond the control of the relevant actors. This is clearly not applicable for the research. Strategic scenarios, on the other hand, aim on internal factors while being aware of the presence of the external factors. The strategic scenarios provide an overview of the variety of consequences of strategic decisions. Considering the development of the hydrogen value chain and the influence of actor decisions on the development of this system, the characteristics of the strategic scenarios perfectly suit the research objective.

Although the explorative scenario approach does not imply to be having a specific desired outcome, visions can be used in addition to describe the desirable futures of actors to be explored by the scenario approach (Stojanović, Mitković, & Mitković, 2014). The visions present narrative outlines of the future system, in this case the hydrogen value chain. Scenarios help to quantify possible outcomes for this these visions. There are two types of visions; visions developed by individuals or visions produced by large actor groups. The second type result in roadmaps or transition pathways (William McDowall & Eames, 2006).

2.2.3 Framework harmonizing long-term transitions and dominance of actor network

Following the two previous sections, the qualitative strengths of visions and the quantitative power of scenarios should thus be combined in one framework that determines a dominant role for the actor network. Hughes applies this in a framework for exploring low-carbon futures. He identifies three different scenario approaches, which are deviations of the explorative scenario approach (Hughes, 2013):

- Trend-based scenario approach
- Actor-based scenario approach
- Technical feasibility approach

The trend-based approach determines possible futures out of trends that are projected by the current system. These trends can be referred to as the perspectives of the actors in the present system. The actor-based scenario approach covers the perspective that the future system is developed by the interactions between the actors in the network. Lastly, the technical approach designs a system in such way that it provides the output needed.

As Hughes states, the technical approach and, sometimes, the trend-based approach are covering the majority of the researches on low-carbon systems and scenarios. This is the reason why the literature is providing so many quantitative and qualitative descriptions of the future systems but does not present interesting findings about how these future systems are to be developed and composed by interconnections between, and decisions of, system actors (Hughes, 2013). This finding was also concluded during the literature study.

Therefore, Hughes provides a way that combines the three scenario approaches in one framework with three interconnected levels. In this way, the framework enables to analyse what decisions are required in the near term to facilitate fulfilment of policy goals in the long-term. This connection between long-term goals and near-term decisions is derived by an actor-based systems perspective. The iteration between the three levels is crucial while moving through time by explorative pathways (Hughes, 2013).

Thus, the framework of Hughes describes an order of determining long-term goals and, thereafter, start analysing actions of actors that influence the future system. These actions are affected by the interactions between the actors. This requires a comprehensive actor analysis, but the framework lacks proper techniques to do so. The actor network is the core level of the framework and should provide clarity about potential roles of actors in determining the directions of the transition pathways.

The ‘technical network’ level, in this thesis identified as the hydrogen value chain, is designed by actions played out in the actor network level that influence systemic change. Subsequently, the technological changes in the hydrogen value chain can be analysed based on their effect on decisions in the actor network. This dynamic results in an iterative loop between the value chain level and the actor network level. The final outcome of the hydrogen value chain needs to be described by a quantitative model. This model is not specified in the framework.

To prevent the framework from being restricted to only actor dynamics, it is opened up to deeper systemic changes in the ‘visions’ level. These visions could result among other things from political principles, general strategies, relative role of state and market, acceptance of certain technologies or services, or visions on utilization of value chain technologies. If the visions are accepted and integrated in the policy agenda, they can influence the actions and decisions in the

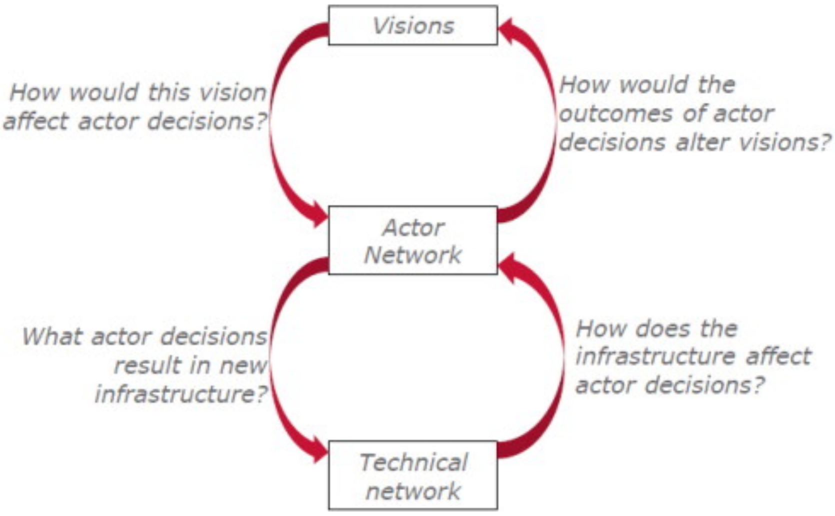

Figure 6: *Three-level framework of Hughes (Hughes, 2013).*

actor network and, thereby, the development of the value chain. On the other hand, the visions are identified by conducting interviews in the actor network level.

For the framework of Hughes, it is critical that the visions are not directly determining the end-visions of the transition pathways, but that they are drivers that affect the dynamics in the actor network level. The decisions and actions of the system actors set the fundament for the final outcomes in the end-visions (Hughes, 2013). The ongoing iteration between the three levels, as presented in *figure 6*, will produce the required information for transition pathways. The iteration is guided by the four questions presented in the figure. A general approach for the construction of the transition pathways is not substantiated.

To recuperate, the pathways towards long-term oriented goals can be a crucial tool in connecting the issues of long-term concern to near-term policy and actor decisions and actions. To benefit from this potential, an in-depth analysis of perceived issues is required. The analysis of the issues supports the identification of 'lock-in' effects in the pathways, which are critical to the development of large socio-technical systems. Lock-in is the phenomenon that 'decisions in the near term have ramifications lasting decades' (Hughes, 2013). The identification of these effects will increase the value of generalised recommendations for policy makers.

2.3 Complementary theories for the framework

The framework of Hughes provides the three-levelled structure for the research in this paper. However, as introduced in the previous section, it needs complementation of theories and models to be able to fully capture the content for the main research question. Extra theories are required for the actor network analysis, the transition pathways and issue determination. For these gaps, complementary theories will be introduced in this section, so that in *section 2.4*, a comprehensive research framework can be presented.

2.3.1 Actor network theory

The multi-actor network is the dominant level in the research framework; the regime level where permanent change of the energy system originates (*section 2.2.1*). The theory describes different regimes between which interactions occur, presented in *figure 7*. To understand the dynamics in the transition of socio-technical systems, the mutual development of these regimes should be understood (Geels, 2004). Actor groups sharing common rules and tasks can be composed and used for further analysis. This forms the basic actor analysis of the current situation in the hydrogen system. The general structure of an actor network and description of the dynamics in regimes can help to understand the composition of the future actor network of the hydrogen value chain.

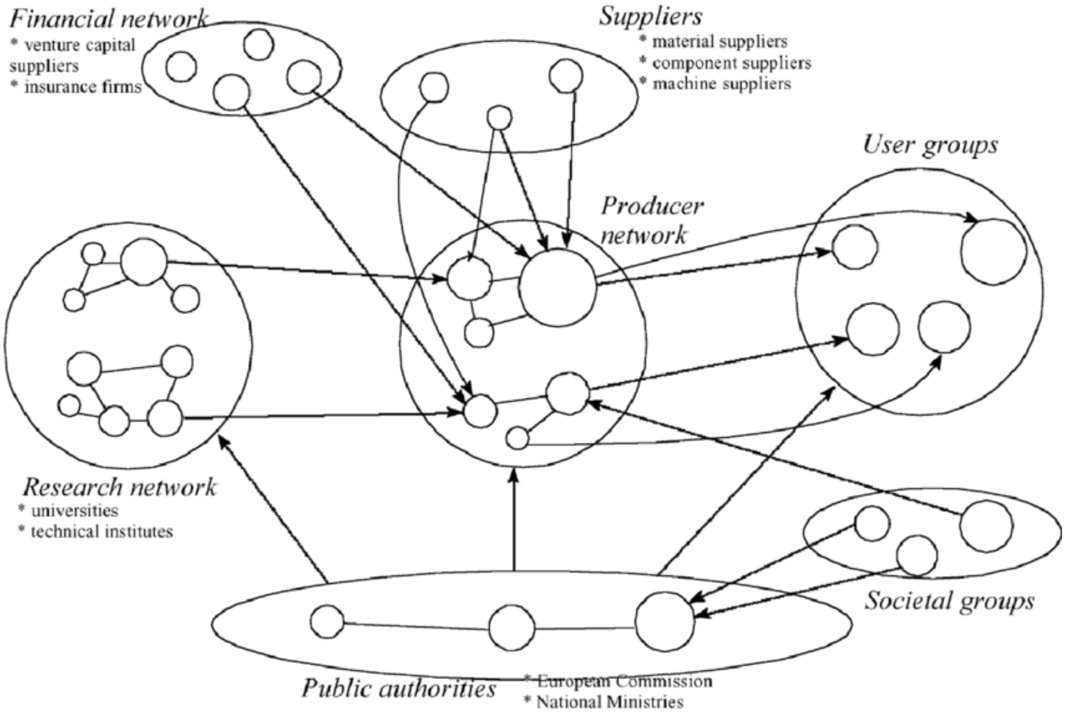

Figure 7: *General structure of actor regime network in socio-technical systems (Geels, 2002).*

The aim of this research is to provide viable transition pathways. Therefore, it is crucial to investigate the influence of the actor regimes on the formulation of transition pathways. In a transition pathway, regime actors are the main group and the focus is on institutional power struggles, negotiations and adjustment of regime rules (Geels & Schot, 2007). The current situation provides the perspective and understanding that supports the construction of pathways. Formulating transition pathways is an approach consisting of three elements (Foxon, 2011):

1. *Characterise the existing energy regime, the internal tensions and landscape pressures on it.*
2. *Identify dynamic processes at the technological niche level.*
3. *Specify interactions giving rise to or strongly influencing transition pathways.*

These elements, specified to the research, form the core steps in the actor network level of the research framework to provide the solid fundament for the exploration of the transition pathways later on. The techniques and methods filling in the steps in this approach are elaborated on in *section 2.5*.

2.3.2 Transition pathway theory

Geels & Schot developed a 'typology of socio-technical transition pathways based on different multi-level perspectives'. They distinguish between four different transition pathways (Geels & Schot, 2007): *transformation*, *reconfiguration*, *technological substitution* and *de-alignment and re-alignment pathway*.

Transitions may start with one particular path but change over time to another or others. The transformation pathway starts when the innovations and technologies are not developed sufficiently to be fully integrated. At this moment, the actors in the regime start by altering and adjusting the direction of the development paths (Geels & Schot, 2007). This research positions the development of the hydrogen system in this phase. The technologies still need improvement, but what technologies will receive the focus in the development can be shaped by strategic decisions that network actors are about to make in the near-term.

The developed pathways aim to describe the processes and actions that realize the transition to the low-carbon energy regime. This relates to technologies, institutions, strategies and consumer efforts. Foxon describes the aspects that should be assessed in the designed transition pathways as follows, specified to this research (Foxon, Hammond, & Pearson, 2010):

- The role of different actors (large, small, public, private) in influencing the pathway (*key actor dynamics*)
- The key technological and social actions that are involved in each pathway and the key engineering and social challenges that arise (*pathway-specific and general transition challenges and actions*)
- The extent of the leadership role of Rotterdam and the Netherlands in both technological and political terms. (*role of PoR*)

These three key aspects constitute the background for the qualitative storyline of the transition pathways developed in this research. This storyline is complemented by a quantitative end-vision that the pathways explore. The balance between quantitative and qualitative information prevent the threat of 'informational bias or plain omission in a roadmap (Hugh, Roche, & Bennett, 2007).

2.3.3 Transition issues

While developing the transition pathways in a system transition, issues are likely to come across. These issues can relate to a variety of system elements, i.e. leadership, policies, behaviour, energy security, governance etc. (Will McDowall, 2014; C. Wang, Engels, & Wang, 2018). However, they can also apply to the full systems transition.

In both qualitative and quantitative, normative and explorative research, issues should be addressed at a general level in the design of transition pathways. Although ex post assessment is always required, it is often more useful to consider the issues ex ante (Söderholm, Hildingsson,

(Hydrogen Council, 2020)	*(IEA, 2019b)*	*(Ministry of Economic Affairs and Climate Policy, 2020a)*	*(Haeseldonckx & D'haeseleer, 2007)*
Investment	Long-term targets	Sustainability of final consumption	Centralised vs decentralised
Policy alignment	Demand creation	Cost reduction and scaling up green hydrogen	Transportational vs overall hydrogen use
Market creation	Investment risk mitigation	Legislation and regulation	Qualitative vs quantitative
	R&D and knowledge sharing	Supporting and flanking policy	Long-term vs short-term thinking and solutions
	Harmonising blending standards		

Table 1: *General issues derived from literature.*

Johansson, Khan, & Wilhelmsson, 2011). The transition pathways exhibit a particular focus on governance patterns. Governance patterns refer to the dynamics between all different actor types in the system and enable the researcher to explore how social, political, technical, institutional, economical and temporal issues affect expected future systemic changes (Foxon et al., 2010).

Actions and challenges should be assigned to the issues that result from the actors' view on the transition process. By analysing the issues faced in the constructed transition pathways, the most relevant lock-in effects can be defined as generalised conclusion in this research. With the determination of the lock-in effects, the feedback loop is generated to the framework of Hughes, after fulfilling the necessary side paths in terms of the issues and transition pathway analysis.

To obtain a general view on what issues could come across and to be able to steer the actor consultation in an effective way, a literature study is performed on up-to-date strategy reports and qualitative studies, i.e. reports of IEA, Hydrogen Council and the Ministry of Economic Affairs and Climate Policy. After data collection and analysis, issues can be further concretized case-specifically (Hydrogen Council, 2020; IEA, 2019b; Ministry of Economic Affairs and Climate Policy, 2020a). The general issues are defined in *table 1*.

2.4 Research framework

The research framework is constituted by the three-level scenario approach that is complemented with extensive transition pathway and actor network theory since the end vision of the hydrogen pipeline network in the value chain is uncertain but can be shaped by human choice and action. Therefore, it requires interactive and participative methods (Mietzner & Reger, 2005). This aligns with the core of this research that is formed to envisage stakeholder participation in the full hydrogen chain to explore dynamics in the transition pathways (Börjeson et al., 2006). The framework is presented in *figure 8*.

The aim of the framework is to meet the challenge of describing the long-term system impacts and outlooks by near-term decision making and actor perspectives. The desire for the comprehensive description of long-term system impacts is the reason transition pathway theory is included to complement and strengthen the research framework. In the transition to a sustainable energy system there is an urge to let the system comply with up-to-date policy strategies and goals (Ministry of Economic Affairs and Climate Policy, 2020a; van Wijk & Wouters, 2019). Therefore, the current policy targets, climate-goals, project plans and scenarios are components assumed to influence visions and, thus, the end-visions and the transition pathways. In the coming chapters, this will be further concretized. For now, the following terminology for the research framework is defined.

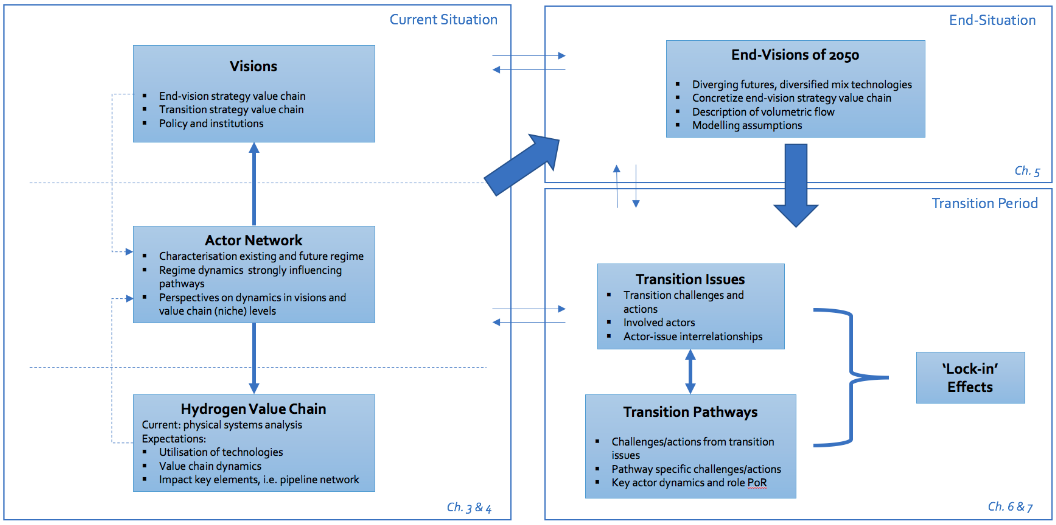

Figure 8: *The research framework.*

- *Scenarios.* Scenarios present the boundaries of the design space in which expectations or prognoses can be constructed. The scenarios result in quantified baselines increasing the viability of the constructed end-visions.

- *Visions.* The visions level includes the governance and institutional mechanisms contributing to the routes towards the projected end-visions, and the general strategies and political targets influencing the dynamics in the actor network and, thus, the outlook of the hydrogen value chain. The elements included in the visions level are mostly starting points for changes in the other two levels.

- *Actor network.* It constitutes necessary actor decisions and involvement. The outline of this level presents an overview of what actors have influence in the development of the pathway and the outlook of the value chain. They are the key link between the policies and strategies in the visions level and the realisation in the hydrogen value chain level.

- *Hydrogen value chain.* This level constitutes the key technological implementation and combination of elements necessary to reach the projected end-situation. The specific focus in this value chain is on the activities around the pipeline network and its link between supply and demand.

- *End-vision.* The constructed visualisation of the hydrogen system in 2050 based on the analysis of actor perspectives on the expected future.

- *Transition issues*. Generalised system issues being faced in the transition period towards a comprehensive hydrogen value chain.
- *Transition pathways*. The routes towards the end-visions, constituting decisions and actions in the visions, actor network and hydrogen value chain level are referred to as the transition pathways. Important note is that the transition pathways are constructed from a systems perspective (William McDowall & Eames, 2006; United Nations, 2015).
- *Lock-in effects*. The near-term decisions with long-term impact. The effects are constituted as the key aspects of the pipeline network, affected by short-term decisions, that are having long-term influence on the development of the value chain.

As presented in *figure 8*, the research framework is constituted by components divided over three analytical points in time between which is iteratively switched to continuously improve the outputs. In the current situation, the first step is to understand the current hydrogen system as it is organised now. As Hughes argues, the possible futures are determined out of trends that are projected by the current system. This requires an analysis of the current system. After that, the framework of Hughes is further applied and the dynamics between the three levels are described and analysed. This process determines the possibilities for the design of the future hydrogen value chain. These two steps are covered in sq. 2 & 3.

Now, all necessary information is acquired to start exploring future expectations and three end-visions are determined for the hydrogen system in the Netherlands in 2050 (sq. 4). With the defined end-visions on the horizon, the transition period can be explored. The actor perspectives on possible end-visions of the value chain result in transition issues to be faced (sq. 5).

Subsequently, the varying transition pathways should be explored towards these constructed end-visions. The divergence of the pathways should obtain relevant insights in the wide range of necessary actions, strategic decisions and dynamics experienced at the three framework levels. Generalising the pathways specific results, provides the determination of lock-in effects that provide remarks for further research and other projects (sq. 6). The divergence of the pathways and sequence of the design process is presented in *figure 9*.

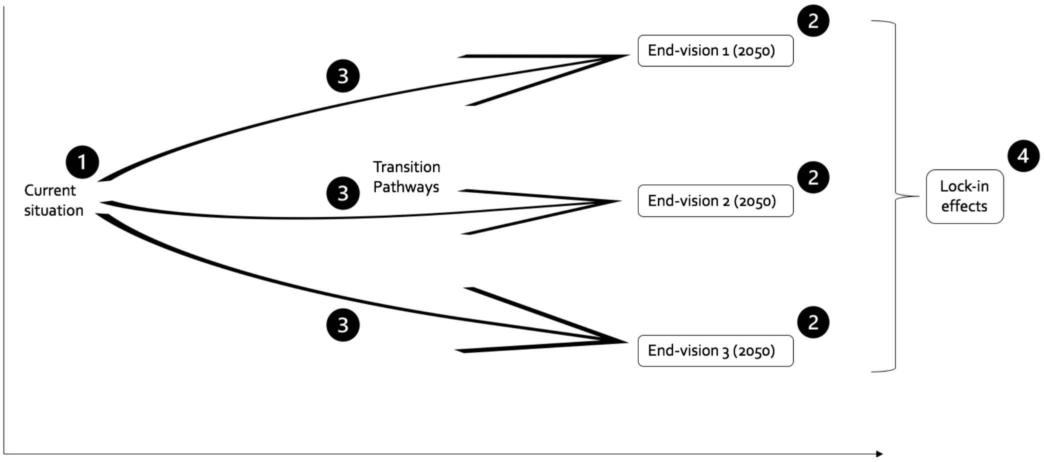

Figure 9: *Schematic outline of the sequential process of the analytical process of the research.*

As to be observed in the research framework, the emphasis in the relation between the three levels in the current situation, is set on the arrows heading from the actor network to the other two levels. This contradicts the theory of Hughes, where the influence of the visions and value chain level on the actor network receive equal attention as the influence the other way around. This simplification in the research framework is due to the limited timeframe in which this research is conducted.

As described in the next section, the empirical data collection method is actor interviews. To determine the impact of the visions level and technical value chain design on the actor network, multiple interview rounds or participatory workshops would be required to obtain a dynamic analysis. Due to the time constraints, the dynamics in the three levels are explored based on the analysis of actor perceptions in the current situation. This implies a static and less elaborate analysis than ideally desired but should still provide very relevant insights based on the current actor perceptions. The long-term impacts are explored by analysing the short-term decisions and perspectives.

2.5 Research methods

This research applies a qualitative scenario approach, which is explorative by nature since the outlook of the hydrogen value chain and the pipeline network is undefined. However, to enable a structured outline, three quantitative end-visions are composed. The pathways towards these end-visions are normative by nature since they describe how a specific target can be reached.

> *'Qualitative scenarios are primarily based on the intuitive logics and explorative modes of future thinking, including stakeholder deliberations and creative thinking, that originate from strategic planning approaches. They explore alterations in the broader socio-political context'* (Söderholm et al., 2011).

The qualitative approach enables the transition pathways to draw explicit differentiations between various strategic decisions since it is not restricted to exact data (Ochieng, 2009). It provides the possibility to understand a complex reality and the meaning of actions in a given context (Queirós, Faria, & Almeida, 2017). During the qualitative analysis, special attention is paid to the difficulty to control variables and the quality of the answers. For the qualitative study, the critical aspect is to obtain the right cause-effect connections (Queirós et al., 2017).

In the following sections, the methods and tools for all chapters, related to the framework components and sub questions, are discussed. The first sub question, listed in *section 1.3*, is answered in by this chapter.

2.5.1 Systems analysis

To describe the dynamics in the three levels in the 'current situation block' of the research framework, first a comprehensive understanding of the current situation and, thus, the (physical) hydrogen system is required. This phase provides the input for, following the applied theory of Foxon in *section 2.3.1*, the characterisation of the existing energy regime:

Sub question 2

What is the outlook of the current hydrogen system, in both the Netherlands and the ICR, and what are relevant future value chain elements to consider in exploring the development of the pipeline network?

The technical and organisational description of the system is obtained by doing mostly desktop research. In order to describe the transition, an extensive analysis of all the system components expected to be utilized in the future value chain should be done. The relevant technologies for the Netherlands and Rotterdam, according to reports and policy documents, are outlined. It provides the base for the investigation of the transition from natural gas to hydrogen and the development of the value chain. This is part of the conceptual and exploratory phase of the research. Skills obtained by learning systems thinking analysis and techno-economic analysis will help to provide and structure the information that is collected in this stage.

The output of this phase is the description of the current and future system, and the specification of value chain elements that can be used to construct the end-visions. The future systems exploration defines the system tasks to which actor groups should be assigned.

2.5.2 Actor network and perspectives on visions and value chain

In *chapter 4*, the actor network level and the impact of the actor network on the visions and value chain level is analysed:

Sub question 3

How do the actor network dynamics influence the transition period, and what are the actor perspectives on the development of the hydrogen value chain and visions, focusing on the pipeline network?

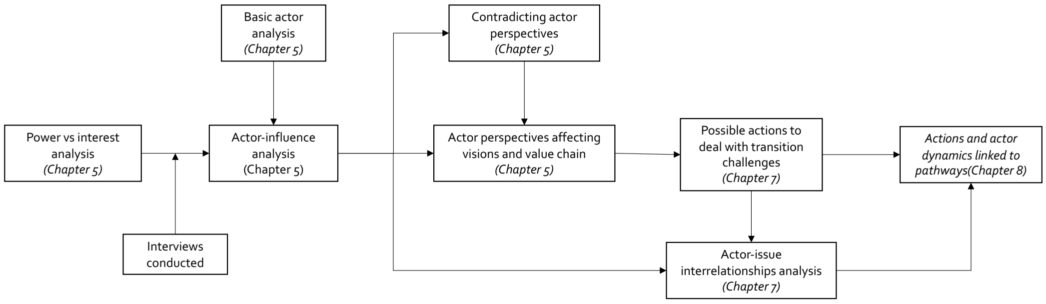

Figure 10: *The actor analysis framework that flows through the iterative process of the research.*

In this empirical and analytical phase, semi-structured interviews are the general data collection method. To determine the selection of actors for the interviews and to analyse the data, several actor analysis techniques are applied. Following *section 2.3.1*, the basic actor analysis first describes actor roles, interests, objectives and perceived problems and the power vs interest grid defines the selection of actors for the interviews. This covers the first aspect in the research framework: *characterise the existing energy regime and its internal tensions and pressures on it.*

Thereafter, more detailed actor analysis techniques are applied, of which some of them in chapter 7 and 8. The techniques are used to support the analysis on the *interactions strongly influencing the transition pathways* and the perspectives on *processes at the value chain and visions level*. Literature describes a very extensive series of techniques that correlate the actor analysis to the other framework elements, i.e. issues, transition pathways, visions and value chain (Bryson, 2004; Eden & Ackermann, 2013; Hermans & Thissen, 2009). This flow of techniques is presented in *figure 10*. The actor-influence diagram supports the identification of key decision areas (Eden & Ackermann, 2013). The other actor analyses result in the recognition of problems regarding the value chain dynamics and actor perspectives on both strategies in the visions level and the technical utilization of value chain elements. The recognized problems require strategic solutions to guide the pathways. The actor-issues interrelationships analysis will be included in *chapter 7*.

2.5.3 End-visions for 2050

The projected end-visions for 2050 are constructed in *chapter 5* and are improved with the knowledge and information derived on the different actor perspectives during the interviews.

Sub question 4
What are, based on the actor perspectives, three viable end-visions for the hydrogen value chain in 2050?

This phase uses the techno-economic output of the systems analysis, complemented by the perceptions of actors on the future systems design. The baseline of the end-visions, that is used to open-up the discussion during the interviews, is provided by analysing a wide variety in strategy reports and scenario reports, listed in *appendix C*. Following the research framework, the end-visions should present diverging quantified futures with a diversified mix of technologies and a focus on the volumetric flow. All modelling assumptions should be monitored.

The base of the end-vision will be in qualitative form supported by quantitative visualisations since the objective is to gather views from experts and policy makers on these possible future societal developments as well as to enable stakeholders to ‘think’ about this socio-technical issue (Alcamo, 2008). To present reliable and representative visions of the end-situation and to obtain relevant outcomes, the deployment of production and demand sectors and the volume flows should be quantified. Quantification allows for a reliable comparison between the end-visions and corresponding pathways in the analytical phase since the same units of analysis are provided. Therefore, the narrative is supported by quantitative information modelled in the Energy Transition Model complemented by calculations in Microsoft Excel if necessary. The Energy Transition Model is further introduced in *chapter 5*.

2.5.4 Transition issues

Sub question 5
What are general transition issues to be faced in the transition towards the hydrogen value chain in 2050 and what are the key network actors empowered to deal with them?

The systems transition issues result from the identification of challenges and barriers in the transition period, as perceived by all system actors. Therefore, the input used for this phase is provided by the basic actor analysis and actor perspectives upon the projected end-visions. The desktop research on system transition issues in *section 2.3.3* provided already some aspects currently identified in research and scenario projects. Following the research framework, challenges, actions, actors involved and the relation between the actors and issues are addressed in the issues analysis.

This stage is pure analytical since all the data has already been acquired. It provides insights in the actor perspectives on decisions and actions required to deal with the identified challenges, which serves as input for the transition pathways. The actor-issue interrelationships diagram structures the identification of key actors in the ability to deal with the constructed issues. A common interest or influence on issues also identifies a deeper layer in relationships between the actors (Bryson, 2004).

2.5.5 Transition pathways

Chapter 7 discusses both the transition pathways and the lock-in effects.

Sub question 6

What are possible transition pathways, focussed on actions related to the pipeline network, towards the constituted end-visions for 2050 and what lock-in effects can be defined in the transition?

The transition pathways explore the diverging routes towards the three varying projected end-visions. In this chapter, the method of Foxon on the design of transition pathways is key (Foxon et al., 2010). This method focuses on the challenges and actions regarding general transition issues and the specific pathways, and on key actor dynamics and the role for the PoR in international context. By applying this focus, the transition pathways let explore the route towards the end-visions. Therefore, causal logic is applied to combine all the generated data and analyses from the previous steps in constructive pathways. After having interviewed actors over the full width of the value chain that are directly impacted by, or have direct influence on the pipeline network, it is ensured that the systems perspective is fully investigated. Therefore, from the three diverging pathways, the general lock-in effects can be concluded.

2.6 Conclusions

This chapter answered the first sub question by providing a constructive research framework consisting of all elements required to explore the evolvement of a hydrogen pipeline network, as a crucial part of the hydrogen value chain, towards 2050. The framework combines the long-term vision exploration in socio-technical transitions with a dominant role for the actor network in the analysis of the transition process. The three-levelled fundament of the framework, provided by Hughes, combines a visions approach, actor-based approach and technical feasibility approach. By extending the framework with comprehensive actor network analysis and transition pathway theory, of Geels and Foxon, and with transition issues, based on theory of Foxon and McDowall, a unique approach is designed that contributes to the type of research currently conducted by combining perspectives not applied before.

Chapter 3

Systems analysis

This chapter introduces the current hydrogen system and the generic description of the expected relevant future system elements for the ICR and the Netherlands. For all system elements, there is elaborated on their current and expected state of technology and economics. The reports used for this systems analysis are presented in *appendix C*. The area of focus is the ICR, including the port, and the Netherlands, but sometimes European or global information is used to set the context or due to lacking regional data. This approach will support the answer to sub question 2:

What is the outlook of the current hydrogen system, in both the Netherlands and the ICR, and what are relevant future value chain elements to consider in exploring the development of the pipeline network?

3.1 Introduction

3.1.1 Physical properties hydrogen

The physical properties of hydrogen vary significantly from those of natural gas, as presented in *table 2*. The lower density of hydrogen desires roughly 3 times larger volumes to supply the same energy demand as natural gas. This requires larger pipelines or pipelines with higher pressure, and thus a faster flow, and larger storage units (IEA, 2019b).

Property	*Hydrogen*	*Comparison to natural gas*
Density (gaseous state)	0.09 kg/m^3	1/10 of natural gas
Density (liquid state)	70.79 kg/m^3	1/6 of natural gas
Boiling point	-252.76 °C	90 °below LNG
Energy density (ambient cond., LHV	0.01 MJ/L	1/3 of natural gas
Specific energy (gaseous, LHV)	120 MJ/kg	50 MJ/kg
Specific energy (liquified, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x of methane
Ignition energy	0.02 MJ	1/10 of methane

Table 2: *Physical properties of hydrogen compared to relevant equivalent forms of natural gas (IEA, 2019b).*

In liquid state, hydrogen obtains a higher energy density than in gaseous form, but conversion processes are very energy-consuming due to the very low boiling point, thus should always be thought through carefully. Maintaining the liquid state over long periods of time, possibly during overseas transport, is not worth the costs in many occasions. This is incomparable with the liquefaction of natural gas and directly impacts the feasibility of the international intercontinental market that requires transport overseas.

3.1.2 Contribution of hydrogen in energy system

Hydrogen is expected to deliver some crucial services in the energy- and feedstock-system for the middle-term (2030) and long-term (2050) (H-vision, 2019; Rijksoverheid, 2019):

- *Zero-carbon feedstock for process industry*. Current knowledge provides no alternatives.
- *Zero-carbon energy carrier for high-grade heating in industr*y. Replacement of high-temperature process fuels as natural gas, refinery fuel gasses and naphtha cracker gas in petrochemical industry. Alternatives are limited.
- *Flexibility for the volatile renewable energy production* by providing seasonal storage and energy transport over longer distances. As a power generation fuel, it could replace coal and natural gas.
- *Mobility*. Passenger transport for longer distances and heavy-duty transport, such as shipping and aviation sector.
- *Built environment*. For locations that experience difficulty in decarbonisation by alternatives.

An element that is missing in the list presented above, but included in more recent policy statements, is the role for hydrogen in the international energy market. The future import and export of energy in the Netherlands that is to be decarbonized as well. Both economically (export/transit) and from the perspective of security of supply (import) of the national energy system, hydrogen is expected to be the decarbonized gaseous energy carrier replacing natural gas and oil (Ministry of Economic Affairs and Climate Policy, 2020a). The import and export is especially reserved a central role in the vision of the Port of Rotterdam, but this will be outlined in further detail in *section 3.4* (Port of Rotterdam, 2019).

3.2 Current hydrogen system

Currently, the hydrogen value chain in the Netherlands is not mature and only developed as an industrial point-to-point supply chain. The volume flow of hydrogen in this system is sufficient for the current industrial application but is not by any means in proportion to the future prospected demand.

3.2.1 General information

The Industrial Cluster Rotterdam (ICR) constitutes ca. 60 companies of which five oil refineries and 36 chemical processing companies. These companies together consume 260 PJ energy in their production processes and are responsible for 18.6 Mton CO_2 emissions annually (Port of Rotterdam, 2018). This final energy consumption of 260 PJ comprises 117 PJ natural gas

Industrial cluster	*Hydrogen production*
Delfzijl	1.3 billion m^3
Geleen	1.8 billion m^3
Ijmuiden	1.0 billion m^3
Rotterdam/Zeeland	6.1 billion m^3

Table 3: *Allocation of hydrogen among industrial clusters in the Netherlands.*

consumption for industrial processes, 30 PJ for power production and 120 PJ of energy that is extracted from residual gasses. Hydrogen is, nowadays, primarily used as a feedstock and is produced from natural gas by Steam Methane Reforming (SMR), and in some cases by Autothermal Reforming (ATR). However, substituting or converting the above mentioned streams of natural gas and residual gasses to zero-carbon hydrogen could reduce the emitted CO_2 by 12-15 Mton annually (H-vision, 2019).

3.2.2 Volumes of the current system

In the Netherlands, the hydrogen market is estimated at 9-10 billion m^3 per year, which corresponds to 0.8-0.9 Mton hydrogen, compared to a European demand of 7 Mton. This is an annual hydrogen production of 96-107 PJ (CE Delft, 2018b). The demand in the hydrogen market is built up by 60% ammonia industry and 40% (petro)chemical industry. What can be observed, is that the share of the petro-chemical industry in the total hydrogen demand is much higher in the Netherlands compared to the rest of Europe, which is among others caused by the specific industrial activity in Rotterdam. The hydrogen is produced mainly by reforming processes using natural gas, 80%, while the remaining 20% originates from the (electro-)chemical industry where hydrogen is produced as a by-product. The total hydrogen production emits 12.5 Mton CO_2, however this is partly reused by performing Carbon Capture and Utilization (CCU) in connection with the horticulture and soda drinks industry (Berenschot and TNO, 2017). The annual hydrogen production in the Netherlands is divided among the industrial clusters as presented in *table 3* (from *table 2*, it can be calculated that for hydrogen in gaseous state, 1 billion m^3 contains roughly 10,7 PJ energy) (DNV GL, 2017).

The industrial clusters of Rotterdam and Zeeland are combined in this overview since they are connected by the pipeline of Air Liquide, which even connects them to Belgium and Northern France.

3.2.3 Network infrastructure

The currently operated hydrogen network consists of pipelines within the ICR and transmission pipelines connecting the industry in Rotterdam with industry in Zeeland, Belgium and Northern France. The hydrogen grid of Air Liquide has a total length of 1000 km and 140 km of these pipelines is also operated by Air Products (CE Delft, 2018a). In the Ruhr-area in Germany, Air Liquide operates a similar hydrogen network, but there is no interconnection between these two networks yet. Only in the Ruhr-area and in Rotterdam, the density of consumers is sufficient to operate such a finely meshed grid in a cost-effective way.

Since the volumes in the network of Air Liquide and Air Products are of reasonable amounts and both the supply and demand of the industrial companies connected to the grid are of baseload, storage options are not yet applicable. When needed, the pressure can be reduced or increased a little to serve as storage mechanism, this is called line packing.

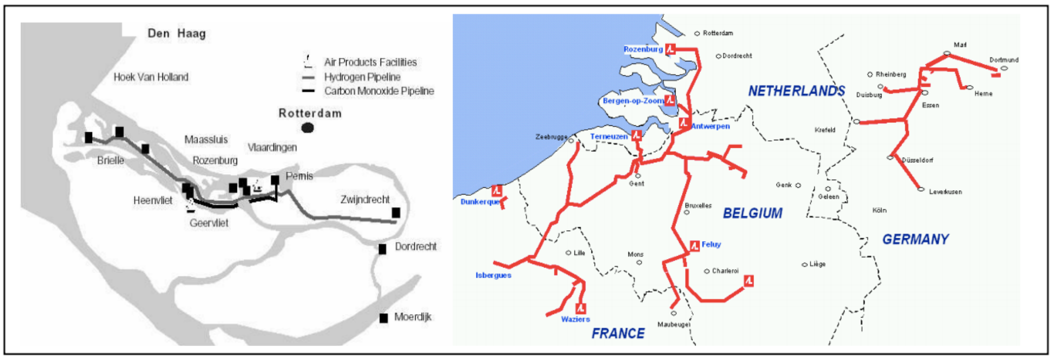

Figure 11: *Hydrogen pipeline infrastructure of Air Products (left) and Air Liquide (right) (DNV GL, 2017).*

These networks are privately owned and operated, and the physical network infrastructure is designed in such way that it can facilitate the transport as agreed upon in the bilateral contracts of the included parties. When looking at the expectations regarding the increase in hydrogen demand towards 2030 and 2050, it is not expected that these pipeline networks can organize the future transport as well. Therefore, to facilitate upscaling of the production and demand for hydrogen, a new network serving higher capacities is required (CE Delft, 2018a).

3.2.4 Current systems diagram

In the current situation, the production and most of the consumption of hydrogen is originated in the industrial sector. In this sector, a distinction should be made on the purity of the hydrogen that is required for the specific demand applications since this affects the layout of the chain upstream. This results in two separated hydrogen systems, where the first represents the flow of 'pure' hydrogen from electrolysis and the second constitutes the cycle of hydrogen produced from natural gas.

From the volume flows and network infrastructure design, the current hydrogen system for the industrial cluster in the Port of Rotterdam in *figure 12* is constructed (Berenschot and TNO, 2017; H-vision, 2019; Samadi et al., 2016; TKI Nieuw Gas, 2017). It clearly shows two separate systems, currently operated in the Netherlands and in Rotterdam. A flow from system 2 to system 1 can be facilitated with purification of hydrogen by PSA, a technology that is further described later on.

System 1

In this supply chain, the hydrogen is produced as a by-product in electro-chemical industrial processes. The highest contribution in this system comes from the hydrogen that is produced during chlor-alkali electrolysis (IEA, 2019b). This hydrogen cannot be labelled as green hydrogen since the electrolysis is powered by electricity that is constituted by the average electricity mix partially supplied by fossil resources. However, this by-product hydrogen is a very 'pure' form of hydrogen, which means that it does not contain shares of other gasses such as methane or nitrogen.

The 'pure' hydrogen is transported by the pipelines of Air Liquide. In the same pipelines, Air Products distributes its hydrogen that is from a significant lower quality. Air Liquide operates

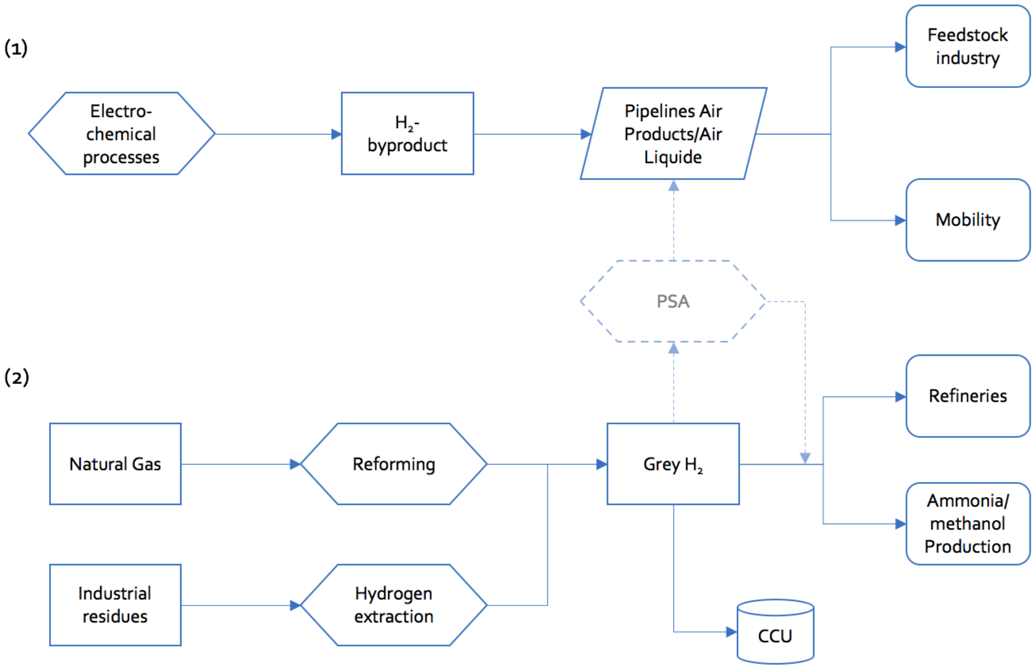

Figure 12: *Organization of the current hydrogen system in the Industrial Cluster of Rotterdam.*

a pressure of roughly 80 bar or more and Air Products maintains a pressure of at most 64 bar. Therefore, the two hydrogen products, varying in level of quality, will not be blended occasionally.

Multiple producers and consumers are connected to the pipeline grid. However, Air Liquide and Air products are owner of both the network and the molecules that flow through the network. This monopolistic organization allows for high quality assurance on both entry and exit of the pipeline network. In principle, the flow in the pipelines between Rotterdam and the other regions is zero, meaning the regions operate independently. However, at occasions or during maintenance, the supply can be guaranteed by the interconnection. The presence of multiple producers and two operators avoids full dependency on one supplier. This organization varies from the publicly operated natural gas network, where the ownership of different system components was separated during the energy market liberalization in the late 90s and early 00s (Cace & Zijlstra, 2003).

The pure quality hydrogen is consumed either as a feedstock in industry or for fuel cells in the mobility sector. These are two demand applications that require hydrogen in its purest form (TKI Nieuw Gas, 2018). A more detailed insight in different demand centres will be given in *section 3.3*.

System 2

While system 1 completely relies on the flow of hydrogen as a by-product from the electro-chemical industry, system 2 has both a flow of hydrogen as by-product from industrial processes and as a main product from the reforming of natural gas. However, where the hydrogen by-product in system 1 is being produced by electrolysis, the residual flow of hydrogen in system 2 comes from steam cracking, naphtha or LPG cracking, petrochemical processes or oil residue gasification (H-vision, 2019; Samadi et al., 2016).

This hydrogen is of a less pure form than the hydrogen that flows in the first system. Therefore, these systems are separated. SMR and ATR techniques are both leaving particles of methane, nitrogen or other molecules in the hydrogen, which result in hydrogen that is not suitable for fuel cells or as feedstock for particular processes. Apart from the purity of the hydrogen, there is another major difference with system 1. The hydrogen is either produced by reforming of natural gas or in industrial processes on site, and is, if needed, transported in a point-to-point pipeline to another industrial company. In this point-to-point pipeline there is no complexity and no need for a network operator. These poin-to-point pipelines are not connected to the pipeline network infrastructure of Air Liquide and Air Products.

In the two major demand centres, the industrial ammonia production (NH_3) and methanol production (CH_3OH), hydrogen is used as a feedstock (ISPT, 2019a). The ammonia production and the oil refineries are the bulk consumers (TKI Nieuw Gas, 2018). The hydrogen in system 2 can be upgraded and further purified using pressure swing adsorption (PSA) to be possibly implemented in the Air Liquide and Air Products network. Although interconnection of the two systems by PSA is technically feasible, it is hardly deployed.

3.3 Future hydrogen system

The main challenge in the future system is the setup of a completely new to be designed value chain in a liberalized market. This value chain constitutes the following components (Noordelijk Innovation Board, 2017):

1. Production
2. Markets
3. Network infrastructure
4. Society

Only by developing these four pillars togethers, the hydrogen economy and its value chain can be built up. The 'society' covers among other things the required regulatory framework, public acceptance, political visions and safeguarding the public interest. In this section, the building blocks of the first three pillars will be covered. The societal aspect is covered by the actor network and transition issues in the coming chapters. The exploration of the future value chain is structured following *figure 13*.

3.3.1 Production

For the production of hydrogen, multiple technologies can be used. Each technology requires different production resources and energy inputs. Based on the level of emissions in the production cycle, the hydrogen output is labelled as either grey, blue or green.

Grey hydrogen cycle

Grey hydrogen is, currently, the only type of dedicated hydrogen production deployed in the Netherlands. The grey hydrogen can be produced by either coal gasification or natural gas reforming. Globally, coal gasification is a well-known production method, although it emits around 4 times the level of CO_2 per kg of hydrogen as compared to reforming plants that are majorly utilized in the Netherlands (Hydrogen Council, 2020). The Netherlands produces,

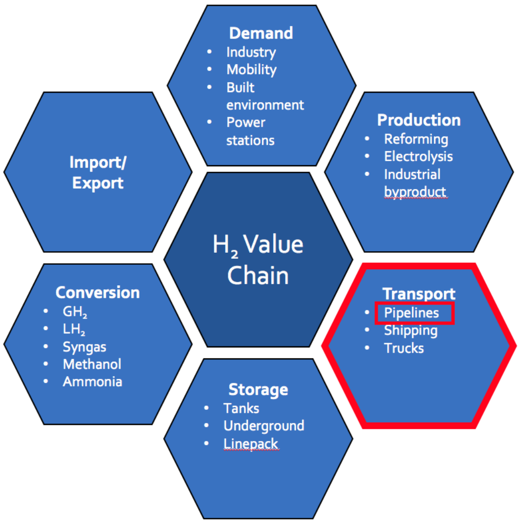

Figure 13: *Building blocks of the hydrogen value chain with the focus on the pipeline network.*

after Germany, the largest volume of grey hydrogen in Europe. It is still the most cost-effective production method of hydrogen, although this largely depends upon the cost price of natural gas and the CO_2 price of the ETS (Ministry of Economic Affairs and Climate Policy, 2020a). Grey hydrogen does not obtain a role in national strategies and plans regarding the energy transition since it does not contribute to the goal of a decarbonized energy system (Provincie Zuid-Holland, 2020).

Blue hydrogen cycle

Blue hydrogen is hydrogen produced from fossil resources, but accompanied with CCS or CCU. In the Netherlands, the fossil resource used is natural gas. In short, the blue hydrogen process flow could be presented as the chain in *figure 14*.

Following the elements as presented in this figure, the natural gas supply, CCS and CCU have no direct impact on the outlook of the hydrogen value chain and the role of pipeline transport in this value chain. Therefore, the elaboration for these elements is presented in *appendix C*.

Reforming

Steam methane reforming (SMR) is a process that combines natural gas and compressed steam to produce syngas. Syngas is a blend of carbon monoxide (CO) and hydrogen; a hydrocarbon. In the SMR process, producers are able to capture roughly 60% of the CO_2 in relatively easy manner, by separating the carbon dioxide from the hydrogen. The rest of the CO_2, up to 90%, can be captured at the end stage of the process. However, this extraction is much more expensive than the first 60% (Hydrogen Council, 2020). Currently, the production costs of SMR are in the range of €1-1.50/kg hydrogen for large scale facilities. Smaller scale sites produce hydrogen between €4-5/kg, but this range is expected to be lowered by €1/kg towards 2030 (TKI Nieuw Gas, 2018).

Autothermal reforming (ATR) also produces a syngas, although this process combines natural gas with oxygen. In the ATR process, the carbon capture rate is up to 95% and this is the

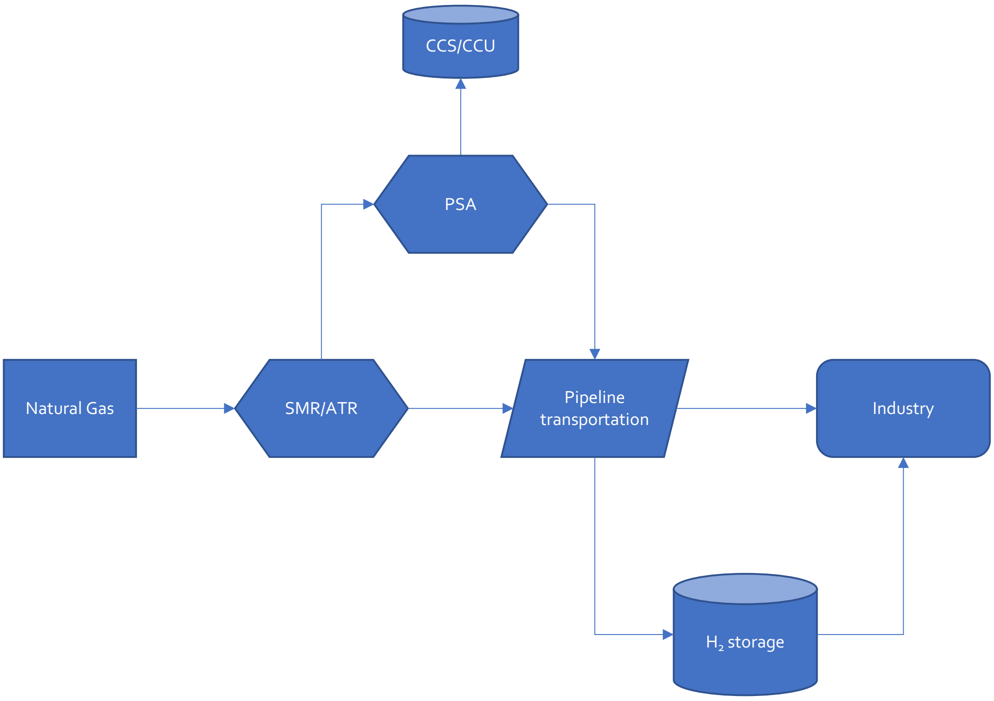

Figure 14: *Blue hydrogen chain (CE Delft, 2018a).*

preferred technology for larger plants. Since the reforming units currently being operated are of minor volumes, the ATR technology is currently less utilized in the industrial sector. Generally, it is expected that SMR will remain the dominant technology because of its favourable economics for smaller units, the fact that it is more deployed nowadays and, therefore, it can realize sizeable production in the short-term (IEA, 2019b; Navigant, 2019). However, the higher capture rate, operational flexibility and the favourable economies of scale of ATR, let some projects decide to plan to operate an ATR unit to minimize the capital expenditures (H-vision, 2019).

	CO_2 capture rate	*CO_2 capture rate per kg H_2*	*Levelized H_2 costs (€/m^3*	*CO_2 avoidance costs (€/kg CO_2*
SMR	85 - 90%	7.7 - 8.1	0.154 - 0.165	0.049 - 0.070
ATR	>90%	8.1	0.143	0.048

Table 4: *Comparison between SMR and ATR (CE Delft, 2018a; TKI Nieuw Gas, 2018).*

PSA

Pressure swing adsorption (PSA) is a technique used to separate gasses and to purify flows and waste flows. Therefore, it can be used in both the capture process of CO_2 and in the purification process of the hydrogen produced by SMR or ATR (Kim, Ko, & Moon, 2016). In this research, there is no need to present an in-depth analysis of how this separation and purification works. However, an understanding of the utilization is relevant since the quality of hydrogen and, therefore, the system standards are related to PSA.

Not necessarily all hydrogen is processed by PSA. Only if low-purity hydrogen in the blue hydrogen cycle is required for end-use appliances in the green hydrogen cycle. PSA can be performed directly after reforming or can be done in smaller units at consumption site. Which alternative is preferred depends on the hydrogen standards in the network infrastructure. After purification by PSA, the blue hydrogen can compete with hydrogen produced by electrolysis since purities of 99.97% can be reached (Relvas, Whitley, Silva, & Mendes, 2018).

The costs of PSA are significant and depend on the composition of the hydrogen to be purified, the volume and required purity. Therefore, during systems design, the empowered actors should determine carefully the location and scale of PSA in the chain to minimize the associated costs.

Green hydrogen cycle

Green hydrogen is hydrogen produced in electrolysers with zero CO_2 emissions throughout the entire production cycle. Therefore, the electricity used in the electrolyser must be supplied by renewable energy sources, such as solar and wind, to adhere to a zero net carbon emission (ISPT, 2019a). In Rotterdam, the North Sea potential offers favourable opportunities for the deployment of offshore wind energy for the electricity supply. This may even result in dedicated offshore wind farms for the production of green hydrogen (Provincie Zuid-Holland, 2020; Wood Mackenzie, 2019).

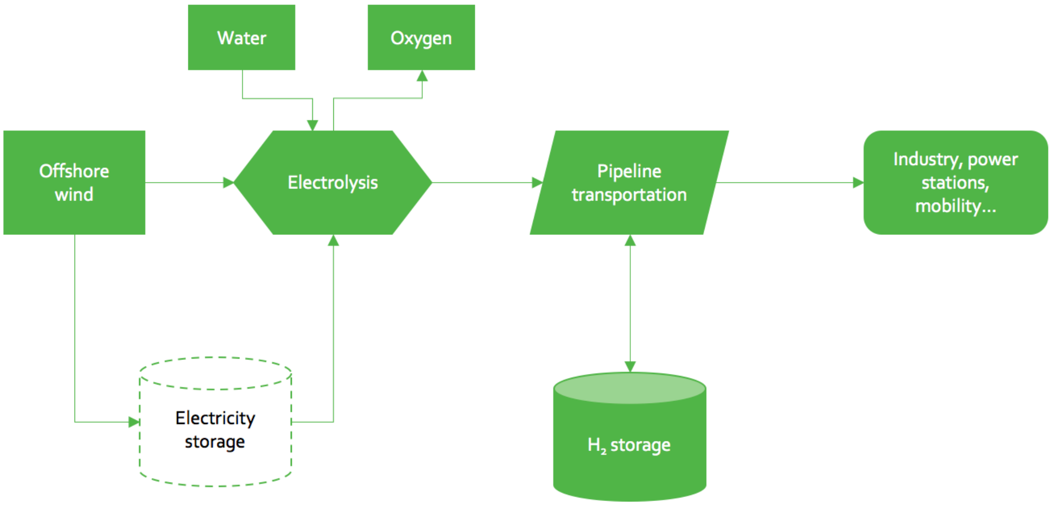

Figure 15: *Green hydrogen chain (CE Delft, 2018b).*

Following the presentation of elements in *figure 15*, offshore wind is only indirectly related to the role of pipeline transportation in the value chain. Therefore, its elaborate analysis is included in *appendix C*.

Electrolysis

Electrolysers produce hydrogen by splitting water molecules (H_2O) in hydrogen (H_2) and oxygen (O) with use of electricity. This is done by alkaline electrolysis or a proton exchange membrane (PEM). Alkaline is the cheapest technology and is able to provide electrolysis on a large scale, however PEM electrolysis offers greater flexibility options. This may be preferred when the electrolyser is connected to a volatile renewable source like offshore wind (CE Delft, 2018b). Offshore wind is a favourable option since the large capacities and its strategic advantages for the Netherlands and Rotterdam. Another option would be to supply the electrolysers with electricity from the average electricity mix. However, using this electricity mix, the hydrogen cannot be labelled as 'green' and the average CO_2 emissions could meet up to 25 kg CO_2/kg H2, dependent on the level of renewables in the mix (IEA, 2019b).

For the Netherlands, TKI Op Zee prospects that P2G units enable market development opportunities. By 2023, 3.5 GW should be operational, and this should be further scaled up to 7 GW by 2030. Assuming an electrolyser efficiency of 66%, the production of a kg hydrogen requires 50 kWh electricity (Berenschot and Kalavasta, 2020; TKI Nieuw Gas, 2018). This determines the production of green hydrogen to be still the least cost-effective option, as presented in *figure 16*.

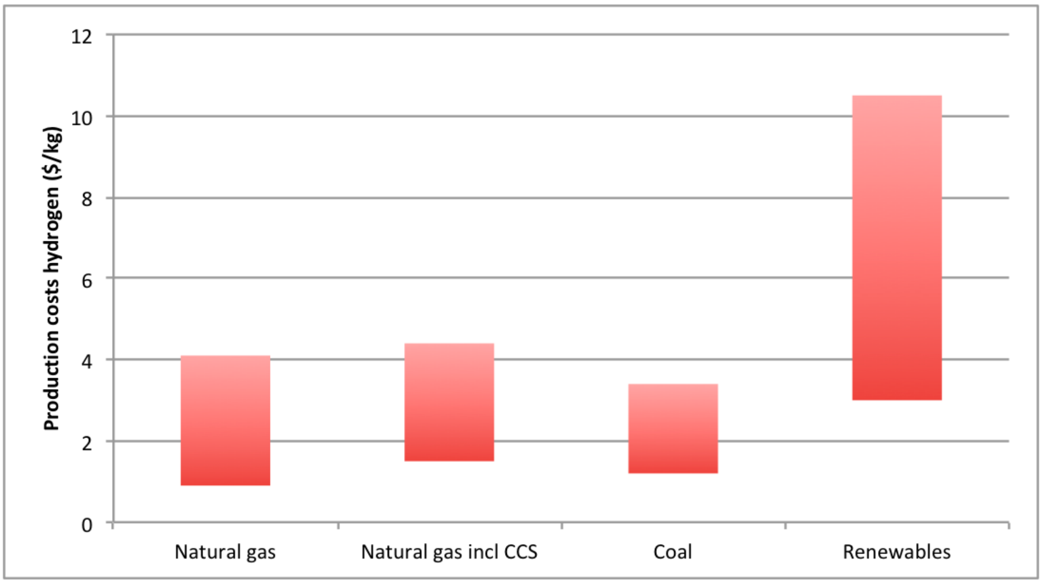

Figure 16: *General production costs nowadays of hydrogen for all sources (IEA, 2019b).*

Although the costs of renewable hydrogen produced from offshore wind in Europe starts at about €5/kg in 2020, the costs are expected to decline to €2-3/kg, driven by scale in electrolyser manufacturing, larger systems and lower-cost renewables (Hydrogen Council, 2020; TKI Nieuw Gas, 2018). The costs of the hydrogen production by electrolysis can be accounted for 87% to the offshore wind production and for 11% to electrolyser costs (IEA, 2019a).

Scenarios presume a large role for offshore wind in Rotterdam because of its strategic location near the North Sea. However, in 2050 the electrolyser capacity in Rotterdam could require around 40 TWh annually (Gasunie and TenneT, 2019). This would desire up to an estimated 11 GW of offshore wind capacity (Rijksoverheid, 2019). In this regard, the limited capacity of the North Sea, as presented in *appendix C*, causes restrictions, and other energetic resources should be considered, such as imported hydrogen or blue hydrogen.

The main challenge faced today with hydrogen produced from electrolysers is the scale of production and high associated costs. Currently operated electrolysers are at most a few MW, while to produce significant volumes of hydrogen that can meet the already high demands in industry, electrolysers of GW-scale are desired. As reference, a hydrogen plant of 200 MW, as announced by Shell for 2023, is expected to generate 20 kton annually, while the total hydrogen demand in industry in Rotterdam is currently 0.4 Mton and could increase to 7 Mton in 2050 (Port of Rotterdam, 2020b).

The investment costs for a GW-scale electrolyser are roughly one billion euros and should be reduced three- or fourfold to become an economically viable alternative for blue and grey hydrogen. Therefore, the goal is to scale up the electrolyser capacity to bring down costs and stimulate innovation (2018).

3.3.2 Network infrastructure

In the development of the hydrogen value chain, multiple transmission and distribution options should be considered since large scale deployment of hydrogen requires an infrastructure that connects suppliers with consumers (TKI Nieuw Gas, 2018). The optimal transportation mode is directly related to the state of the hydrogen carrier. Since this research focuses on the development of transportation pipelines in Rotterdam, the emphasis is on hydrogen in gaseous state. However, liquefied hydrogen, hydrogen in ammonia and the liquid organic hydrogen carriers (LOHC) will sometimes be discussed as they could be required for storage options or to increase the efficiency of the flow of hydrogen in the system.

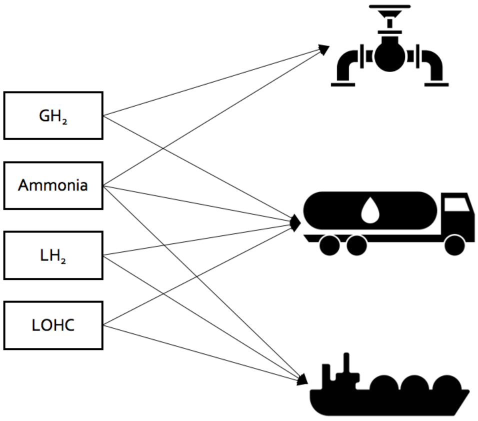

Figure 17: *The relation between the type of hydrogen carrier and possible transmission and distribution alternatives (IEA, 2019b).*

Three alternatives are considered in general for pipeline transport (DNV GL, 2017):

1. Blending hydrogen in natural gas, to be distributed in the existing natural gas grid
2. Reuse of (parts of) the existing natural gas grid for 'pure' hydrogen transport
3. Construction of a new dedicated hydrogen pipeline network

Blending hydrogen into natural gas

At this moment, the permitted share of hydrogen in natural gas is limited because of regulatory restrictions and specifications of end-use appliances. The Dutch gas law only allows for

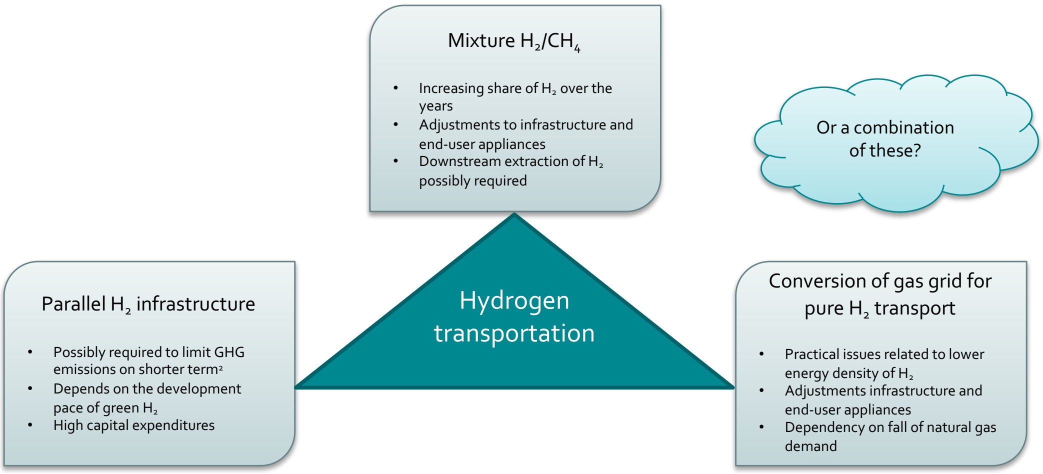

Figure 18: *Overview of the three pipeline transport alternatives.*

a hydrogen share of 0.02 mol%. On the other hand, as also presented in the literature study, many technical studies aimed for percentages up to 20% (Hydrogen Council, 2017). This shows the very high level of uncertainty and heterogeneity in recommendations on this aspect. The experienced difficulty is introduced by varying permittable shares for all elements in the natural gas chain, i.e. compressors, pipelines, gas turbines and end-use appliances, as shown in *figure 19*. Therefore, a solution could be to isolate parts of the grid and to increase the share locally to 20%, 50% or even 100%. Increasing this share, requires adjustments to the appliances with every step and is therefore not expected to be effective (DNV GL, 2017).

Furthermore, complications can be expected regarding the difference in density. The density of hydrogen is 1/10 of the density of natural gas. This causes the hydrogen to flow with a different speed through the pipeline compared to natural gas. By extracting the gas from the pipelines over a period of time, the average share of hydrogen in the gas over that period of time is an agreed number of percentages. However, there could be bulks of hydrogen being extracted with shares up to 100%. This could be fatally damaging for end-use appliances.

The advantage of blending relates to the time frame in which it can be operational and the relatively low capital costs. Blending of a few percentages could be operational on the very short-term. However, once adjustments are required, further considerations should be made on the cost-perspective as well (Hydrogen Council, 2020). Another interesting advantage is to use blending as transition mechanism to start-off the first volume flows. But again, varying blends would ask for flexible end-use appliances, which is expensive and unpractical. Furthermore, the expected development of hydrogen demand and production would require higher volume flows (Navigant, 2019). In this regard, it is not surprisingly observing that especially in the past two years the blending alternative decreased in attractiveness and attention.

If adjustment of end-use appliances is not feasible, extraction of hydrogen at the consumption site is theoretically possible by PSA. However, this is an expensive process since the natural gas also need to be recompressed after extraction of hydrogen. PSA can cost between 3 and 6 USD/kg hydrogen, but this depends on the level of hydrogen in the mixture and the hydrogen purity required by the end-user (IEA, 2019b; Melaina, Antonia, & Penev, 2013).

Reuse of existing gas grid

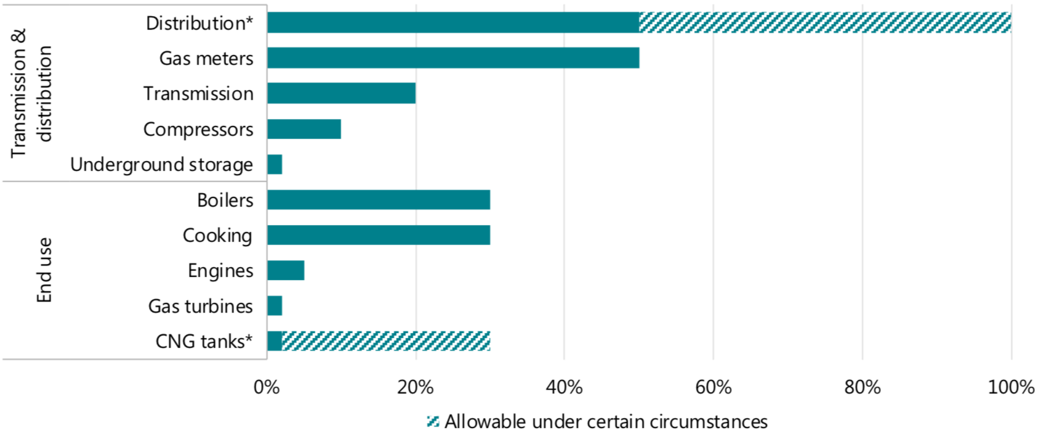

Figure 19: *Permittable share of hydrogen for various system components in the natural gas infrastructure (IEA, 2019b)*

The second alternative for hydrogen transport is the reuse of existing natural gas pipelines and other systems assets. The existing infrastructure can be utilized in two ways (Berenschot and TNO, 2017):

- Using the existing pipelines with necessary adjustments.
- Implementing a new pipeline inside the existing pipelines (pipe-in-pipe)

The high-pressure transmission net is able to deal with a flow of 100% hydrogen in the future. However, modifications should be made on the compressors, metering stations and storage facilities. Apart from that, there are no obstacles regarding technical or economic factors to do so (TKI Nieuw Gas, 2018).

The largest drawbacks on the use of the existing gas grid is the availability and the location of the pipelines. Since the extraction of Groningen gas will be stopped in 2022, the national transmission network, consisting of multiple parallel pipelines, can be made partially available for hydrogen on a short notice. However, the flow of natural gas in the local distribution net, that contains fewer parallel lines, is still required in the coming years. Therefore, other alternatives should be considered.

Using the existing pipelines and corresponding assets is most interesting from an economic and practical perspective. The costs of the pipe-in-pipe alternative are even a factor 10 lower than the costs of a new pipeline. The costs of adjustment of existing pipelines are even expected to be lower than for the pipe-in-pipe (Berenschot and TNO, 2017).

New dedicated pipeline network

This is the alternative with the highest capital costs and should be implemented in case reuse of existing pipelines is not possible because of the drawbacks presented above (Ministry of Economic Affairs and Climate Policy, 2020a). As explained in the section on the current system, there is already an existing dedicated pipeline infrastructure in Rotterdam and the Netherlands. Therefore, it could also be relevant to explore whether a new dedicated infrastructure could be connected to this existing infrastructure of Air Liquide/Air Products and what the requirements or bottlenecks are in this process.

Although the investments costs of this alternative will be high, it will come with the least impracticalities. Therefore, as also said in *figure 18*, it could be that this alternative is implemented to speed up the process if the actor requirements are slowing down the development pace. The organization of the new pipeline infrastructure is to be analysed in the coming chapters based on actor perceptions.

3.3.3 Conversion

Hydrogen can be transported and stored in various compositions.Throughout the supply chain, hydrogen could change its state multiple times. However, this all comes at the expense of energy losses due to conversion. Which hydrogen state is preferred, depends on the type of transport, storage and demand requirements. As already said, the focus on the pipeline network in this research set the general scope to hydrogen in gaseous state, while discussing other forms when necessary.

For the Port of Rotterdam, liquid hydrogen and ammonia are important carriers since they are suitable for intercontinental shipping hydrogen. Possibly, it could replace the LNG/LPG import economy currently present in the Port. Where the conversion of hydrogen to ammonia is a well-established technology, liquefaction of hydrogen is an innovation that needs further research and development (Hydrogen Council, 2020). When hydrogen itself is used as energy to facilitate the liquefaction, the hydrogen would consume between 25% to 35% of its initial energy level (Ohlig & Decker, n.d.). As comparison, natural gas requires roughly 10% of its energy to be liquefied (IEA, 2019b). The high costs for these conversion techniques also require upscaling of the processes to create cost-competitiveness.

When designing the new value chain and weighing all system component alternatives, the impact of conversion costs and losses are not to be neglected. It could be very interesting to liquefy hydrogen in North-Africa, ship it to Rotterdam and convert it back to a gaseous state before it is implemented in the Dutch pipeline network. However, the conversion costs and losses will determine largely whether this path is economically viable indeed.

3.3.4 Storage

As baseload demand volumes increase and hydrogen is introduced as flexibility option for balancing the volatile renewable production, the network coordination will increase in complexity and the need for storage capacity is inevitable. The following options, ordered from small-scale to larger scale in *figure 20*, could be considered. Line packing and salt caverns are the options considered to be most relevant in this near-term (CE Delft, 2018a; Kruck, Crotogino, Prelicz, & Rudolph, 2013; Schiebahn et al., 2015; Smartport, 2019).

Line-packing is the reduction or increase of pressure in the pipelines and thereby adjusting the pace of the flow and the volume supplied to the consumer. This technique can offer buffer capacity only for small daily variations. A disadvantage of this technique is that the energy density of hydrogen is one-third of the energy density of natural gas. Therefore, the line-packing capacity is also three times lower. Also, many pressure changes can reduce the lifetime of the pipelines (DNV GL, 2017).

Salt caverns provide large-scale seasonal storage facilities. Salt caverns offer the most suitable alternative, because of the low storage costs, high volumes and small amount of cushion gas requirements. Cushion gas is the minimum amount of gas that should always be present in the system and that may not be extracted (Robinius et al., 2018). Main disadvantage is the geographic dependency. There are no salt caverns in Rotterdam, so a pipeline connection to the salt caverns in the northern part of the Netherlands is required (Samadi et al., 2016).

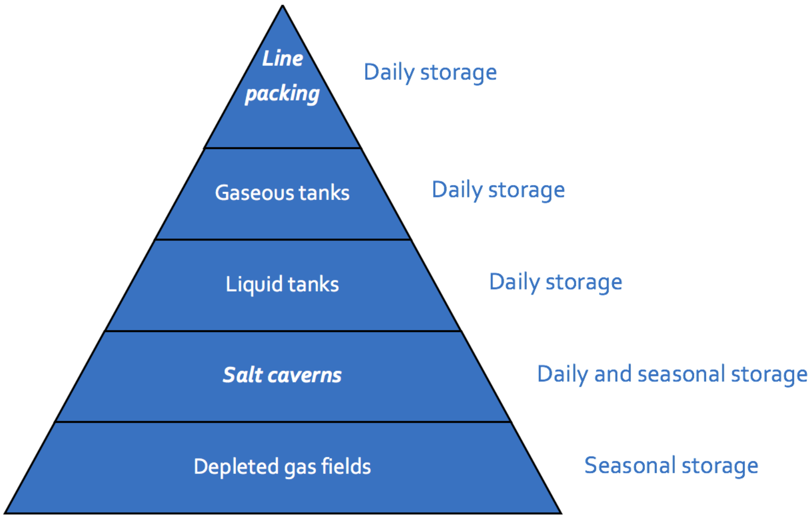

Figure 20: *The various storage options for the future hydrogen system.*

Depleted gas fields have the highest economic potential (Kruck et al., 2013). There are several offshore gas fields located near Rotterdam, so this could be a promising alternative although it is yet unclear whether storage in gas fields is feasible. By widening the design scope to a cross-border level, storage in salt caverns would also be possible in the German Ruhr-area (TNO, 2020). As location, this could be a more favoured connection to facilitate the hydrogen product flow since the Ruhr-area is expected to be one of the largest future consumers of the flow of hydrogen present in the Port of Rotterdam. Actor dynamics, with a strong role for the Dutch network operators, are expected to largely determine what alternative is preferred.

3.3.5 Markets

The goal of the implementation of hydrogen in the demand sectors is the decarbonization of industry, mobility and the built environment. Additionally, hydrogen can serve as buffer capacity in the power sector (Hydrogen Council, 2017). *Chapter 5*, where the end-visions for 2050 are discussed and constructed, will further elaborate on the expected volumes of the different demand sectors.

Industry

The industrial sector is the only sector where the current situation exhibits a hydrogen demand flow. The hydrogen is predominantly used as feedstock in oil refineries and chemical industry. Hydrogen, in general, can be used in industry as a feedstock (raw material), process gas or can be burned to provide high-temperature process heat. It can also be used for low-temperature heat, but in this regard, electrification could be a better alternative. The decarbonization of the industry and the difficulty to apply electrification in some crucial processes determines a dominant role for hydrogen (TKI Nieuw Gas, 2018). The different types of demand require different compositions of hydrogen. Hydrogen used for heating has less stringent requirements for its purity than hydrogen used as feedstock (ISPT, 2019a). The requirements related to the quality of the desired hydrogen directly relates to the deployment of green or blue hydrogen and will be emphasized in depth in the coming chapters.

Mobility

Currently, the most transportation vehicles run on diesel and gasoline. However, since this sector is also looking for decarbonization, battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) are considered. This research will not dive into the specifications of these type of mobility, but generally speaking, hydrogen is preferred for heavy duty transport (Tlili, Mansilla, Frimat, & Perez, 2019). The mobility sector requires hydrogen of the highest purity to burn in the fuel cells. The refuelling infrastructure, however, is way underdeveloped in the Netherlands. Germany is a few steps ahead, but the consumption at these refuelling stations is not yet optimal (IEA, 2019b). Therefore, the market of FCEV's should develop by support of subsidies to drive down the high purchase costs of these cars (Hydrogen Council, 2020). It could be questioned whether a hydrogen pipeline network is required for mobility since the conventional supply is also organized by trucks, while volumes are significant.

Built environment

The Netherlands exhibits a finely meshed infrastructure of natural gas for low-temperature heating in the built environment. In 2050, 7 million houses and one million buildings should receive its energy from a mix without natural gas (Rijksoverheid, 2019). This asks for a major and complex reorganization since the energy demand in the built environment in the Netherlands exists for 71% by heat, of which 87% is supplied by natural gas (EBN, 2019). Electrification is expected to play a predominant role in the energy transition for the built environment. The share of electricity in the final energy consumption will increase, but do has its limits. In optimistic scenarios electricity can acquire a share of 50% in the final energy mix. This means that there will be still a significant need for molecules. Here, hydrogen comes into play (TKI Nieuw Gas, 2020). In this research, it is to be found out what the role of hydrogen in the built environment could be.

Power sector

Hydrogen can serve as an energy carrier to balance the variations between supply and demand in the electricity sector and for long-distance transport (CE Delft, 2018b). The two conversion processes come with significant conversion losses and the efficiencies of the processes are still to be improved in the coming years. The overall process efficiency is around 35%. Also, the capital costs of hydrogen-to-power fuel cells are high and technologies on batteries are improving (IRENA, 2018). Flexible combined cycle gas turbines (CCGT) could also be used, but require modifications and further technological development (TKI Nieuw Gas, 2020). Besides flexible power generation in the centralised electricity production, hydrogen could also be utilized in off-grid power supply and decentralised back-up facilities (IEA, 2019b).

Expected volumes of hydrogen are difficult to provide since it depends on the development of hydrogen in the other sectors and the transition in the electricity system. Although hydrogen offers advantages for the sector, it is a cumbersome roundtrip, with significant losses, to produce hydrogen from electricity and generate power again. It would be more likely to utilize hydrogen in the other sectors and use overshoots in the power sector on occasion. Therefore, only very few countries venture themselves to publish specific targets on hydrogen use in the power sector (IEA, 2019b).

3.4 Import of hydrogen in Rotterdam

For the import of hydrogen, currently, the field considers three alternatives (2020b):

1. Liquid hydrogen; the hydrogen is transported by ship under a temperature of -253 °C.
2. Hydrogen in ammonia; Hydrogen is at production site chemically processed in a reaction with nitrogen to ammonia and imported by ship.
3. Liquid organic hydrogen carrier (LOHC); hydrogen is bonded to other chemical molecules and imported by ship.

To enable import by pipeline, an international network infrastructure is required. For the port of Rotterdam and Dutch companies, there are major possibilities exhibited to gain a strategically interesting position in the hydrogen (transit) chain.

3.5 Projects overview

The national backbone is the interconnection between the five industrial clusters, which is currently still fully exploited for the transport of natural gas, but should enhance upscaling hydrogen volumes in the future as well (**255**). Since the backbone consists of multiple parallel pipelines, some of the pipelines could be made available for the transportation of hydrogen. The planned operation is included in *appendix C*, but should be operational in 2027.

It is expected by the European network operators that the first interconnections between European countries are made between 2025 and 2030, after which network expansion gradually continues (Enagás et al., 2020). The suitability of hydrogen for storage and long-distance transport are promising for the development of an international market that reduces costs and increases volumes.

To align to the national and international backbone presented above, Gasunie also plans to construct a regional backbone in the cluster of Rotterdam. *Figure 21* shows the map of this backbone that should be operational in 2023. From the perspective of Rotterdam, connecting the regional backbone to the national and international infrastructure is an excellent opportunity to strengthen its position as hydrogen hub for Europe (Port of Rotterdam, 2020b).

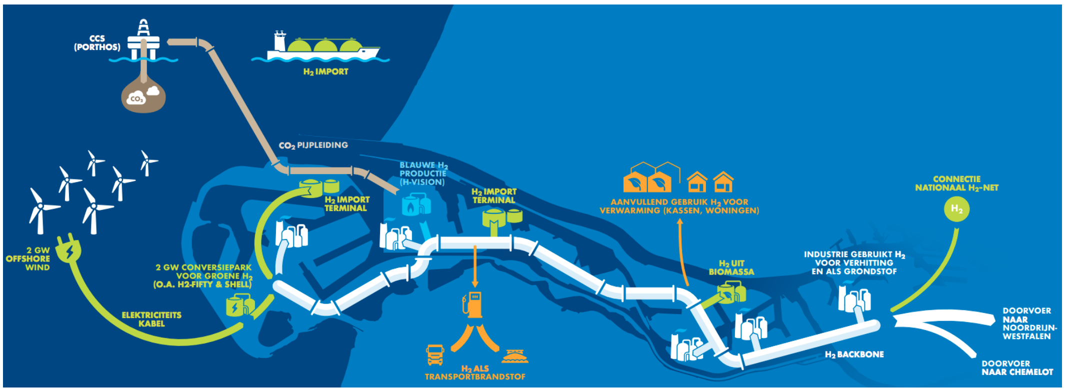

Figure 21: *Presentation of the regional hydrogen backbone of Gasunie in Rotterdam (Port of Rotterdam, n.d.)*

In the *appendix C*, an overview is provided of all planned projects in the industrial cluster of Rotterdam, which could be now and then referred to.

3.6 Conclusions

This chapter constitutes the systems analysis of the current hydrogen system and the technologies most likely to comprise the future hydrogen system, hereby answering the second sub question. It sets the technical scope around the value chain elements that are in the physical system directly connected to the pipeline network. The current systems analysis shows a privatised small-scale hydrogen system operated and controlled by the industrial sector. Two hydrogen cycles are utilized in the current system; the 'grey' cycle is produced by industry at their consumption site, while the green cycle is producing hydrogen as by-product in electrochemical processes and is connected to the pipeline network in the PoR, with connections to Belgium and North-France in case of emergency. For the main pipeline network this means that its owner and operator is the same actor, it only distributes high-purity hydrogen from electrolysis, it supplies one demand sector in one region. Furthermore, the volume flows are relatively small, the hydrogen production is baseload which eliminates the need for storage and there is made use of contracted agreements. The aspects highlighted above determines the current situation to be highly simplified compared to the objected future system, which is expected to be characterized by multiple hydrogen cycles (green and blue), separation of ownership and operation, multiple regions, multiple demand sectors with different purity requirements, large volume flows, open accessibility and volatile production in the case of green hydrogen. This complexity, accompanied by multi-actor problems, will be further investigated in the coming chapters.

To contribute to the goal of decarbonization, the future system is expected to operate a significant flow of green hydrogen. However, the production of hydrogen by electrolysis experiences significant problems regarding the supply of renewable electricity, which requires upscaling of its capacity in alignment with electrolyser capacity. However, to scale up capacity and bring down costs, baseload electricity supply from the average electricity mix may be required, which would increase the full-cycle emissions of green hydrogen.

The design of the pipeline network could make use of three pipeline alternatives. *(1)* Blending experiences difficulties in the variety in blending limits of different system elements. The adjustment of end-use appliances eliminates a dynamic increasing share of hydrogen over the years as possible mechanism. Also, the difference in density and energy density between hydrogen and natural gas are likely to cause problems regarding bulks of hydrogen in the mixture that obtain fatal consequences for end-use appliances and increase difficulty in metering and billing of the gas. *(2)* The reuse of existing natural gas pipelines depends upon the natural gas demand in the coming years and on the location of the available pipelines, which should match the requirements for the hydrogen network. Where the two above mentioned alternatives are favoured in economic terms, the *(3)* new dedicated hydrogen pipeline network is the least cost-effective design solution. However, it constitutes the least impracticalities and dependency on external factors. Also, the connection to the existing hydrogen pipeline network could be considered for new constructed pipelines.

The future systems complexity concluded from the analysis in this chapter will provide the input for the discussion in the semi-structured actor interviews conducted in the next phase. The interviews will collect data on the different point of views from all actors regarding the complexity in the design of the future hydrogen value chain.

Chapter 4

Actor network and perspectives on visions and value chain

The systems' components, as they are described in the previous chapter, can be assigned to systems tasks that are operated by systems actors. First, the basic actor analysis provides insight in the roles and responsibilities in the current and future actor regimes, and what type of actors are expected to fulfil these roles. Then, actor dynamics within the regime level that are influencing the transition are analysed. The chapter is concluded by a summary of all actor perspectives on dynamics in the visions and value chain level of the research framework. Sub question 3 is discussed:

> *How do the actor dynamics influence the transition period, and what are the actor perspectives on the development of the hydrogen value chain and visions, focussing on the pipeline network?*

4.1 Characterisation existing energy regime

The systems analysis concluded that the current hydrogen system is limited in the sense that it is restricted to the industrial sector. In the figure below, the actors of the current system are set out with respect to the pipeline network while keeping in mind the functioning of the system as a whole. In *appendix D*, the background information is provided.

Following the systems analysis, the current hydrogen system is privately owned and operated. Although the network is accessible to any company, the terms and conditions of access are determined by the network operators. By agreeing on the terms with the operators, both producers and consumers can close long-term contracts by which they are allowed to join the system. Producers sell their hydrogen to the network operators in specified volumes and, on the demand side, volumes are bought from the network operators. All volumes are base load and agreed upon in long-term contracts. This implies indeed that the network operators are also owner of the molecules flowing through the pipelines and are responsible for the quality of the hydrogen delivered to the end-consumers. The ownership of both infrastructure and molecules is a construction that would not be possible in a public system due to juridical restrictions designed to prevent monopolistic bottlenecks (Jaag & Trinkner, 2011).

The characterisation of the existing actor regime learns that concerns, regarding the change of the system, relate to the possible loss of dominance by the industrial actors. Especially in

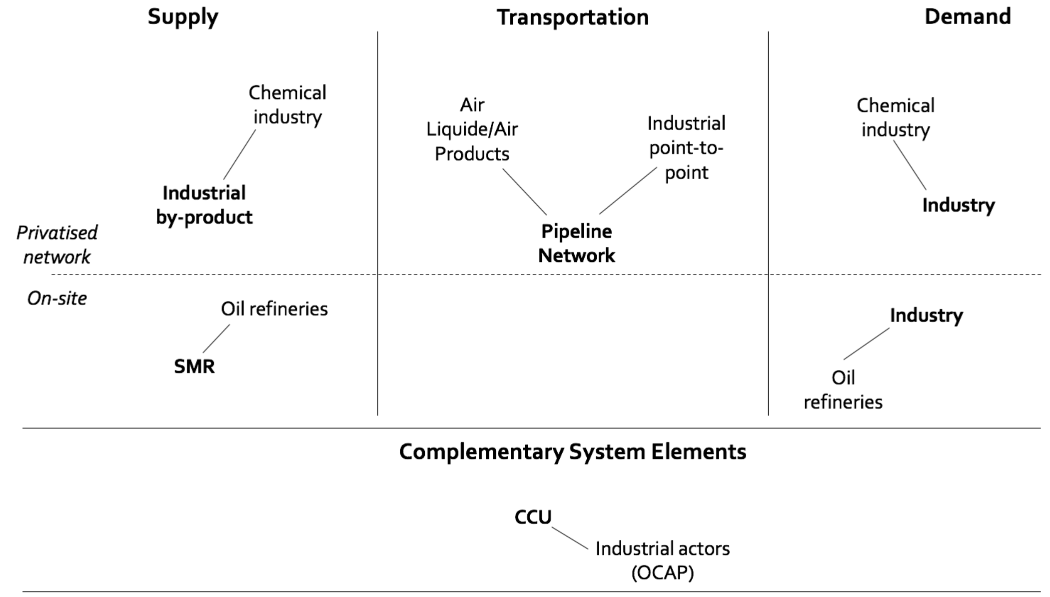

Figure 22: *Characterisation of existing actor regime.*

the perspectives of current network operators, which are also involved in supply and demand processes, suspicion is to be observed regarding the interference of public network operators in their controlled market.

As the systems analysis concluded, there are two 'qualities' or 'purities' of hydrogen being operated resulting in the combination of the blue and green hydrogen cycle in one network. The current privatised network operates high-quality hydrogen and the actors expect problems regarding loss of quality assurance and increase in complexity due to regulation and standards in an open public network.

The current production volumes and network capacities are by no means sufficient to facilitate the expected demand growth. Therefore, the institutional problem of possible (governmental) interference in an existing market is arguably since the existing market is not able to scale up necessary volumes for the future market. Interference is better defined as expansion or separation, in terms of two separately operated markets, i.e. private and public.

4.2 Characterisation future actor regime

In determining the influence of the future actor regime on the transition pathways, one should first describe the future actor network, the actor roles and their dynamics. A distinction can be made for two types of actor roles (Wittmayer, Avelino, van Steenbergen, & Loorbach, 2017):

1. The role of an actor in the transition period (over time)
2. The role of an actor in the end situation (specific point in time)

The system actors maintain their own vision of what the end-situation should look like. However, the route towards the end-situation, and the roles that actors are to play to fulfil this route, are perceived to be uncertain and to change over time. Changing a role of an actor always has implications and consequences for other roles. In the description of the actor network of the future hydrogen system, a separation is made between actors involved in the full process and actors just involved in the transition period. In the transition period, role constellation is observable in the formation of joint ventures and consortia between companies, government, public enterprises and research institutes (Wittmayer et al., 2017).

Furthermore, the development of a new or expanded system allows for the existence of new roles, alteration of existing roles and negotiation on actor responsibilities. An example of possible altering of existing roles through the existence of new roles, could be the introduction of a public transmission and distribution grid operator. This may have serious impact on the role of Air Liquide as it is in the current system. These are dynamics that should be taken note off while looking into the design of a new actor structure. Not paying attention could increase the complexity of the transition and disturb good relations.

4.2.1 Actor selection

The power and interest of the actors is among other things based on the ability to influence the development of the hydrogen value chain and the solutions for the problems experienced (power), and the level of affectedness by these solutions to problematic issues (interest). The actors are clustered based on system tasks.

The actors encircled by the thick blue line, are expected to have a direct influence on the hydrogen pipeline transport development in the Industrial Cluster of Rotterdam. The other actors may have an important role in the development of the full hydrogen supply chain but have an indirect impact on the development of the pipelines. Therefore, the lightly drawn actor types are not defined as indispensable interviewees. Here, for some actors it is explained why they are not considered relevant for an interview.

The potential distributed systems operator (**DSO**) has a high interest in the first stages of pipeline transportation. However, for the coming years, the finely meshed distribution infrastructure is not expected to be a determining component since, first, the backbone and corresponding high-pressure system is expected to develop. Also, the natural gas network in Rotterdam, industrial consumers are connected directly to the high-pressure net and this market is expected to develop first. Therefore, the transmission system operator (**TSO**) is expected to be the most important link. On the other hand, the DSO does have interest in the system because of the possible interconnection and dependency of their low-pressure distribution network to the transmission network.

The **export and power supply** sectors are the only demand sectors left out of scope here. Export is a highly relevant aspect for the Port of Rotterdam, but where import is happening inside the ICR, the interconnections for export are outside the cluster area. Therefore, this aspect is relevant if the scope was widened. Actors taking care of import in the end situation are also not included. However relevant strategic aspects regarding future import are taken care off in the interests of both **governmental bodies** and the **Port of Rotterdam authority**.

For the other demand sectors, as explained above, the **industrial sector** is considered to have the most dominant role since the majority of volumes are expected to be located here. After that, the **mobility sector** is expected to develop small volumes first because of the level of heavy-duty transport in the ICR and few alternative technologies for this sector. The role of the **built environment sector** is important but is expected to be majorly focused on electrification, which is to be further explored during the interviews.

Research institutes have neither high level of power nor of interest. Nevertheless, they possess much knowledge on the system level dynamics of the transition. They have no interest in any business case, which makes them reliable as independent experts. **Governmental bodies** are

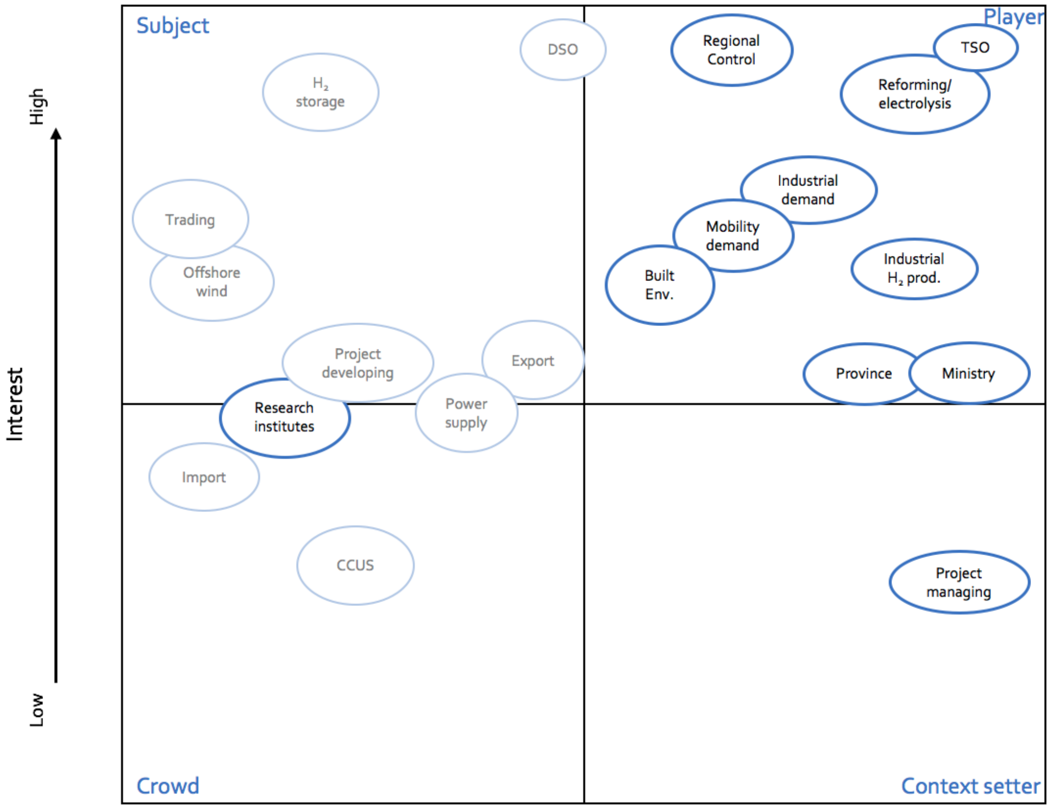

Figure 23: *The power versus interest grid for the future hydrogen system actors from the perspective of the development of pipeline transportation.*

typically characterised as having interest in a decarbonized energy system to achieve the climate agreement target, but exhibit fewer interest in the functioning of the system than enterprises. On the other hand, they possess much power by the ability to issue licences and by implementing legislation.

4.2.2 Problem perceptions future actor regime

The power versus interest grid served as preparation for the interviews by obtaining an understanding of which actors were to be selected. The extensive actor descriptions and their problem perceptions are provided in *appendix D*. Underneath, the perceived problems to be faced in the actor network during the transition are summarized while setting focus on the pipeline network development. The actors included in the figure are the system actors directly influenced or directly impacted by the pipeline network. The PI-grid showed also relevance for project managing and research institutes as experts, but not as key system actors.

Comparing the future actor regime with the existing actor regime, it is easily observable that the multi-actor complexity will increase during the transition period. This brings contradicting perspectives and interests as well as a wide range in perceived problems. Four aspects are highlighted from the regime dynamics presented in as determining factors in the transition period *figure 24*: the public vs private network, the level of control by public actors, the competition

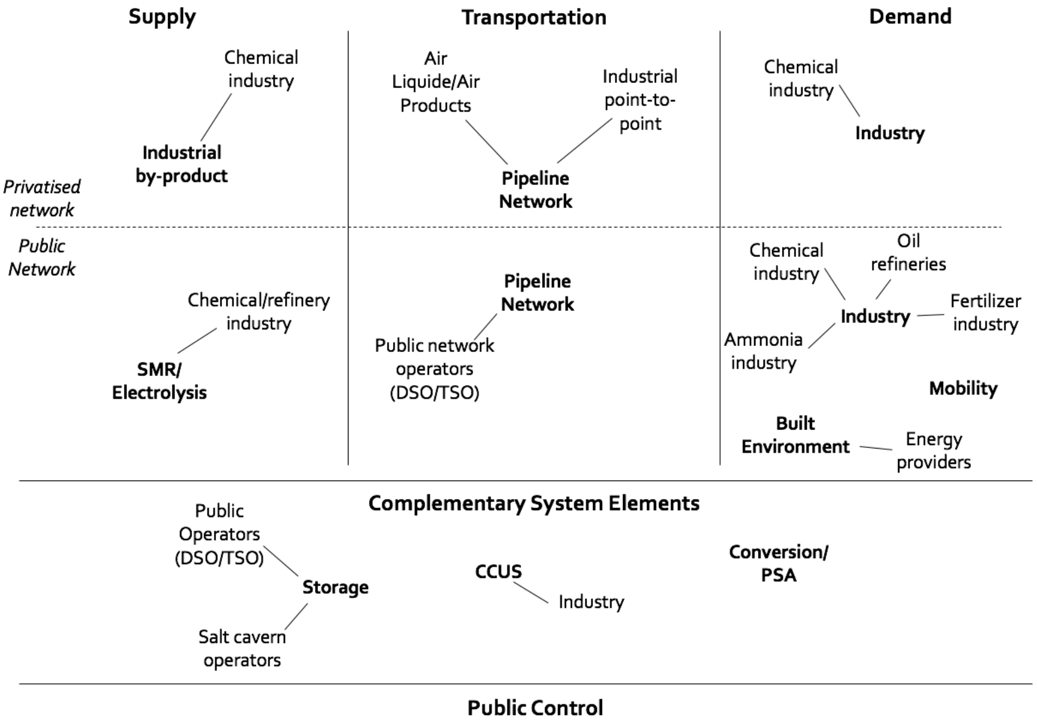

Figure 24: *Characterisation of future actor regime.*

between demand sectors and multi-actor cooperation.

There is separated between the privatised and public network although the transition should explore whether these networks are merged or separately operated. On the other hand, it is not taken for granted that all new pipelines will be publicly owned since industry could benefit from the private operation of crucial pipelines. This is further explored in the transition pathways.

If the public network is designed and capacities are scaled up, the level of required public control inherently increases. This is a new introduced level in the future actor regime and requires careful operation by ministries and provinces. Long-term certainty, by subsidies, is possibly provided for the future actors, while the existing actor regime operates a seamless network without support. This is a sensitive argument.

Although other sectors are expected to enter the hydrogen system, industry still maintains a dominant role since they are influencing processes throughout the full value chain. This introduces the perception by the other sectors that priority is unfairly set in the transition design. The alliance between the high-pressure network operator and the industrial sector is feared to be too strong to enable fair chances in other sectors in the short- and middle-term. The widespread demand volumes in the mobility and built environment sector, compared to the centralised large volumes of industry, are unfavourable arguments.

The complexity of the interdependency of the development of the value chain components is predominating the actor perceptions. This requires an early adoption of strong cooperation in the full range of the actor network. The cooperation can be guided by public enterprises, regional controllers, joint ventures and coalitions.

In the *appendix D*, the presented problems perceived by actors exhibit more problematic aspects, i.e. technological, economic, strategic, institutional etc. These aspects serve as input for the transition issues and will be elaborately discussed in *chapter 6*.

4.3 Actor regime dynamics influencing transition

Section 4.2 introduced a difference between actors in transition period and actors in the end-situation. This section dives deeper into the actor dynamics having influence on the transition period by analysing the actor-influences and contradiction between existing and entering actors.

4.3.1 Actor-influences in transition period

From the power interest grid and the information obtained in the interviews, an actor-influence diagram can be constructed. This sequence is discussed in *chapter 3* (Eden & Ackermann, 2013). The actor-influence diagram captures any formal and informal links and indicates in what way the actors presented in the PI-grid influence each other. The influence is based on actors' responsibilities, roles and expected activities in the transition period. The role in the transition period could differ from the role in the end-situation as described in the previous section. In the actor-influence diagram, performing a centrality analysis and analysing the interconnections between actors obtains valuable insights in the general dynamics between actors in the transition period (Bryson, Cunningham, & Lokkesmoe, 2002).

Figure 25 distinguishes between system tasks, to which the actors are related following the tables in *appendix D*. It shows a clear centralised role for industrial actors and network operators. The connections and dynamics in the diagram will be analysed below.

Industrial production and demand actors have a symmetric influence on all other system tasks. This is caused by the fact that the majority of industrial actors are both producer and consumer of hydrogen since the hydrogen market is currently privatised. The market is small, and the industry is enforced to control and guarantee its own supply. Private point-to-point pipelines between companies or on-site production facilities are the only supply modes. The domination of industrial actors in the current system continues in the transition period.

By observing business reports and the expectations on the actor roles in transition period during the interviews, it is analysed that industrial companies use their power to focus on all elements of the value chain. They dominate the currently planned construction of electrolysers and reformers for the production of hydrogen, they form joint ventures to develop privatised pipelines to roll out their blue hydrogen projects and cooperate in consortia for wind farm tenders (2020; H-vision, 2019). Furthermore, some of the industrial actors are competitors in the mobility sector as well. Presumably, by influencing all value chain elements, their power throughout the system is guaranteed for the end-situation. Aim of industry is to maintain their dominant role of the current system in the future system.

Because of the power in both spectra of the value chain, supply and demand, industrial actors can guarantee the consumption of their own supply; if needed, by contracts with other industrial companies. Since the demand for hydrogen will exceed the supply, at least in the coming years, there is no desire to influence storage tasks.

As cause for the strong central role of the industrial actors, a few factors can be identified:

- Strong urgence to decarbonize and suitability of hydrogen for several elements in industry sector;
- Industry is involved as competitor on both supply and demand side;

- Sufficient capital power available;
- Centralisation of production and demand in industrial clusters;
- High expected demand volumes over manageable number of actors;

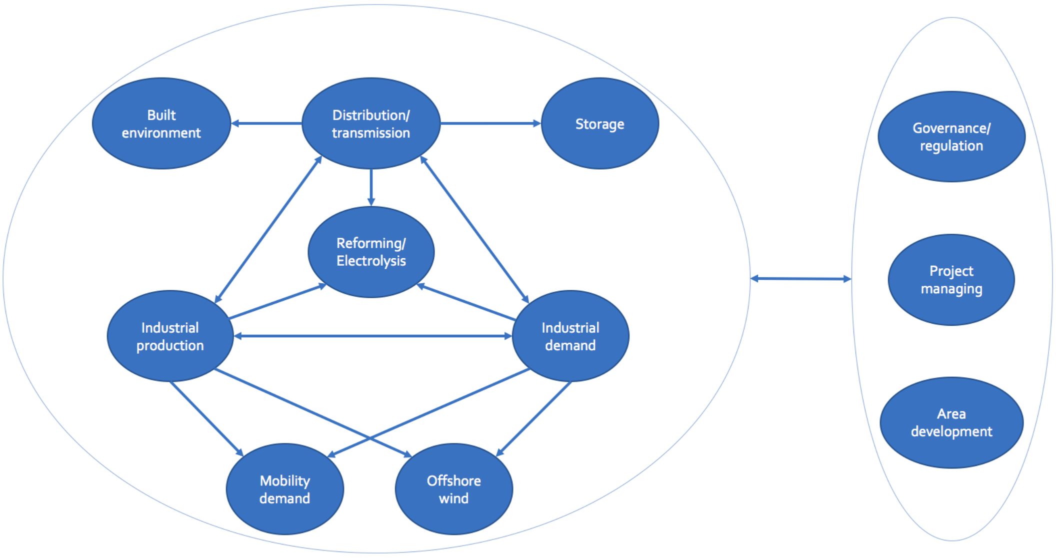

Figure 25: *Actor-influence diagram presenting relations between actors, clustered in system tasks, during transition period.*

The distribution and transmission of hydrogen controlled by public network operators is an entering market task. The public network operators are restricted by law to outperform just the task of operating the network to ensure that this is organized by an independent actor. However, in the transition period, the network operators do focus and cooperate in projects regarding production processes and development of demand markets since the value chain elements require interdependent development. Also, to ensure their own future role as network operator, upscaling of production and demand is required. Whether this is interference of the public network operators in privatised design projects is questioned and perceived as unfair competition by third parties. The public network operators have a second important stake, which is to provide a second life to the existing natural gas pipelines and to reduce their loss of investment in this regard. These aspects of interest, restrict the level of independence that is normally associated with the role of the public network operator, as it is in the current natural gas system. Furthermore, hydrogen is a chemical product and not a common resource, as natural gas is, which further increases the complexity of the market interference of the publicly owned enterprises.

The mobility demand receives less attention by network operators due to its lower suitability for pipeline transport. The built environment perceives interest by the DSO. However, as currently experienced, the built environment sector and the DSO are dependent upon the activities of the TSO, which favours the industrial sector since the industry is directly connected to the high-pressure grid. Therefore, the arrow towards the built environment is one-way. The division of responsibilities between DSOs and TSO is still open for discussion.

Mutual influence is observed between the two clusters in the diagram in *figure 25*. The actors included in the cluster on the right side are facilitating the transition, either to safeguard public interest (area development and governance/regulation) or to design effective business cases as a joint venture (project managing). Their role diminishes as the end-situation is to be reached. Regarding the roles of the system actors on the left in the end-situation, a lot of uncertainty is experienced. This division of responsibilities should be agreed upon by the system actors themselves.

4.3.2 Existing vs entering actors

As argued in the previous section, the current dominant system actors aim to be frontrunners in the value chain development and, thereby, prolong their dominant role in the future systems end-situation. The positioning of existing actors and entrance of new actors cause contradicting perspectives on several fundamental aspects regarding the development of the value chain (*figure 26*).

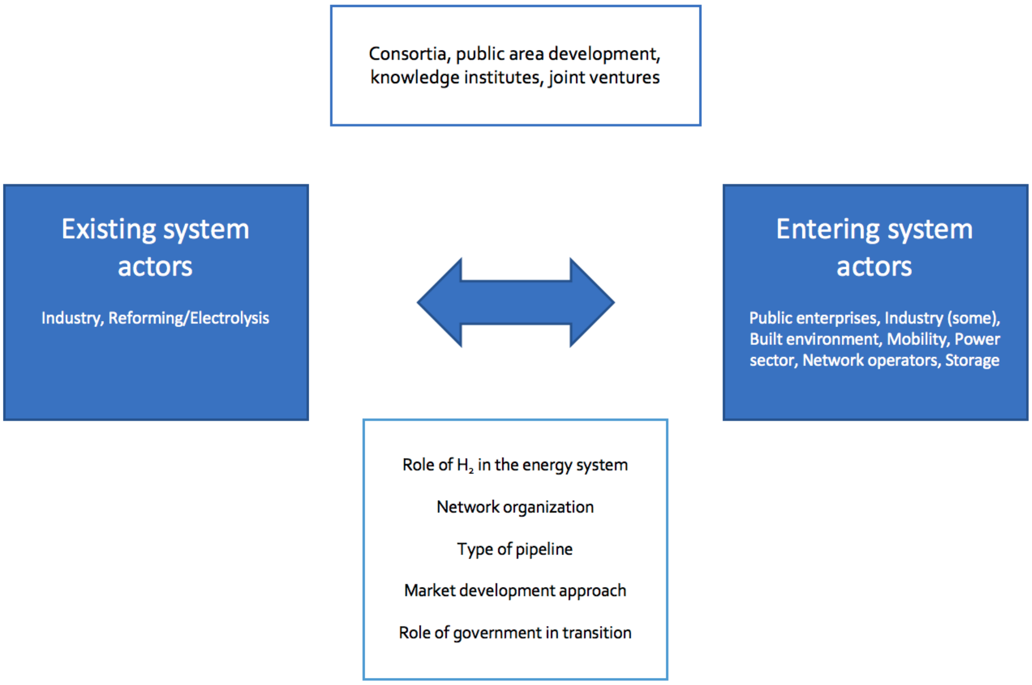

Figure 26: *The contradicting perspectives on fundamental system aspects between existing and entering system actors..*

This is the general consensus after interviewing all relevant system actors. Some actors could also be situated at both sides since they operate as competitor in multiple markets. Where hydrogen is targeted by existing market parties as energy carrier for heat (replacement of natural gas) and as chemical product or feedstock, the entering market parties describe the application of hydrogen majorly for heat and possibly as fuel for the mobility sector. This varying perspective on application of hydrogen directly relates to the purity of hydrogen and, thus, to the type of production. For the business case of existing market parties, it would be interesting to maintain a certain level of control, which increases the interest in a private network or at least the self-management of some crucial pipelines. For entering market parties, benefitting from the investment capacity of public network operators is preferred.

The interviews showed that the extensive natural gas infrastructure of the Netherlands incentivizes public network operators to prioritize the reuse of the existing infrastructure. For existing market actors, already operating in dedicated pipelines, this priority is less acknowledged. Although reuse of the existing network saves investment, political and practical hurdles are experienced causing uncertainties and delays that could be avoided by constructing dedicated pipelines. The actors argued that this choice has already been made in, for instance, the H-vision project.

Where the existing market actors argue that the industrial sector should be starting off on the best footing, entering market actors widen their scope also to other sectors to create an open public system. The required order and scale of development in the other market sectors is uncertain and is further delineated in the transition pathways.

For the future value chain, the existing market actors argue during the interviews that they exhibit the power of investment and the role of the government should be predominantly based on incentivizing. If the government takes a leading role, there is the threat of interference in an existing market, while the market is able to take care of it. The entering market actors presume a more active role of the government and the public enterprises, since this is required in the energy transition (Loorbach, Van der Brugge, & Taanman, 2008). By a leading role of the government and provinces, the investment power of decentralised system actors, for instance the citizens in the built environment, can be exploited.

To compromise on these general contradictions, public and private and existing and entering system actors cooperate in consortia and joint ventures. Also, governmental institutes aim to facilitate systems design where all requirements are safeguarded. The following section and chapter 7 & 8 further elaborate on the systems perspective resulting from the different actor perspectives.

4.4 Actor perspectives

The actor perspectives are, according to the research framework, separated on two aspects:

- The actor perspectives on the visions
- The actor perspectives on the value chain elements and their dynamics

The full description of the perspectives is provided in the tables in *appendix E*, including perceived benefits and bottlenecks of value chain elements, perspectives on the strategic application of value chain elements in transition period and end-situation, and the relation between the elements and the pipeline network in particular. In the following two sections, the most relevant aspects influencing the construction of the transition pathways are outlined.

4.4.1 Actor perspectives on visions

Following the research framework, the perspectives on visions should be divided over 3 aspects: the end-vision strategy for the value chain, the transition strategy for the value chain and the policy and institutions. The findings in *table 22* in *appendix E* are structured on the value chain elements. The key findings are discussed here.

End-vision strategy value chain

For the end-vision, it is essential to determine what demand function hydrogen is to be served in the long-run and relate this to the corresponding type of production. The decisions should outline whether the majority of hydrogen is serving as replacement of natural gas, as source for heat, or if it serves the non-energetic industrial appliances and fuel cells. If hydrogen is to replace natural gas, decision makers must think about a possible role for blue hydrogen in the system, where the second scenario encourages strong deployment of green hydrogen. This is concluded based on purity requirements of the value chain elements; a critical aspect in the future value chain as determined from the interviews. Defining the function of hydrogen in the end-visions for 2050 is directly related to the decision regarding what sectors are to be actively involved at what time in the design process. A combined strategy is also one of the possibilities, although it significantly increases the value chain complexity.

The function of hydrogen in its own hydrogen value chain also has consequences for the functioning of hydrogen in the wider energy system, i.e. as flexibility mechanism in the electricity sector for instance. This is to be considered in design choices as well.

In the long-term strategy of the value chain design, the system actors should thoroughly consider the role of the international market in the development of the national and regional value chain. Significant cost reductions and volume development is expected to be realised at the international market. The aim to benefit from the internationalisation could have consequences for domestic investment decisions. Also, the international market exhibits uncertainty due to dependence on multiple external factors, such as foreign policies and development of conversion technologies required to transport the hydrogen overseas.

Transition strategy value chain

At the production side, the decision paradigm observed is whether blue hydrogen is required as transition mean to fulfil the preferred transition to green hydrogen. The Netherlands obtain the favourable location and knowledge to operate blue hydrogen due to their experience with natural gas and CCS possibilities under the North Sea. On the other hand, since green hydrogen is perceived as optimal solution for end-visions, investments in blue hydrogen could be regarded as ‘loss of resource’. Investments in blue hydrogen can also be defined as indirect support for the development of green hydrogen, in terms of upscaling of volumes and capacities, and corresponding cost reductions. However, the actor perspectives do not provide full consensus on the required transition approach on supply and demand side. Conversion technologies, such as PSA, can provide the link between the two flows of hydrogen, especially in the transition period.

For the pipeline network, the design depends on the international focus of the transition strategy and on whether the volume flows are of such significance that salt cavern storage is required. In this case, connections to regional and national backbones are desired. The preferred strategy is to utilize the existing natural gas pipelines where possible. This will be further elaborated on in the dynamics of the value chain.

Policy and institutions

Since hydrogen is by no means competitive in the first years of the transition period, policy mechanisms are essential in making progress. In the actor perspectives on the visions, several policy and institutional aspects are covered. In the upscaling of volumes and reduction of cost price, virtual blending and SDE++ are most referred to. Virtual blending is relatively easy to implement, accepted by the market and generates public investment capacity. SDE++ are subsidy rounds to incentivize investment in zero-carbon projects, which does implicate that blue hydrogen projects cannot lay claim on this mechanism since they do not fulfil the requirements. This requires attention.

To facilitate a consistent transition strategy towards the long-term end-vision, consistent energy transition policy is essential. This aspect is covered unanimously in all market actor perspectives, by claiming that it is currently lacking. Dependent on the strategy chosen, investments in green or blue hydrogen value chain elements can be incentivized. The level of domestic investment, again, depends on the level of active internationalisation of the value chain.

Apart from incentivizing volumes on supply and demand side, institutional guidance is required in the organisation of the pipeline network ownership, as introduced in the problem perceptions of the future actor regime in *section 4.2*. The actor perspectives are not unanimously in whether the network should be privately or publicly operated. However, a consistent planning is required so that network standards can be designed, and certainty is created for investment decisions and business cases. The function of hydrogen determines the purity that is operated in the network and affects the business cases aiming to provide cost-analyses on whether investment in SMR, electrolysis, PSA and CCS is beneficial.

4.4.2 Actor perspectives on value chain

As described in the research framework, the actor perspectives should be structured on the utilisation of technologies, the value chain dynamics and the role of the key element, i.e. the pipeline network. In this section, the most important findings for the construction of the transition pathways are discussed. The full range of actor perspectives is provided in *appendix E*.

Utilisation of technologies

The utilisation of technologies depends above all on the desired end-vision and designed transition strategy. General consensus among the actor perspectives is that the green hydrogen cycle, with production by electrolysis with input from offshore wind is the preferred supply mechanism because of its possible zero-carbon character. The generated supply volumes should be sufficient in the long run to serve as source for heat as well, although lower purity hydrogen also suffices this type of end-use. The utilisation of value chain technologies exhibits a strong level of interdependence.

Value chain dynamics

Where the blue hydrogen cycle can produce at baseload due to natural gas as resource, green hydrogen has a volatile production and requires storage capacity to serve the baseload demand. In the most efficient network, in terms of energy flow, two supply cycles are operated. The blue hydrogen cycle serves the heating processes and the green hydrogen cycle serves the non-energetic industry and fuel cells in mobility. In such system, no ‘good quality’ hydrogen is wasted for ‘low-quality’ demand appliances. However, several factors, of which the costs and operation of the pipeline network is a dominant one, requires the two cycles to be combined in one system. Combining these two cycles, in one cycle, determines concessions to be made somewhere in the value chain in the form of conversion or purification steps. Either centralised facilities at supply side or decentralised facilities at demand side are required to enable the combination of all functionalities of hydrogen in one system. The pipeline network, operating one standard, is perceived as the determining factor in this decision process, although the type of pipeline was considered not highly relevant during the interviews.

Besides the two cycles of green and blue hydrogen to be combined in the hydrogen network, the imported ‘yellow hydrogen’ cycle is also of crucial importance to the future hydrogen flow in the ICR and the Netherlands. This hydrogen from solar-rich geographical areas can be imported in various states as explained in the systems analysis in *chapter 3*. The extent of the share of imported hydrogen also affects the required conversion steps and standard of the system since it is expected to diminish the role of blue hydrogen as the transition period moves forward. This could opt for a switch in the purity of the major hydrogen flow in the system at a given point in time.

Impact on pipeline network

Analysing the causality in the two hydrogen cycles, green and blue, enables to conclude some impacts on the pipeline network from the utilisation of the value chain elements. First of all, the actors are unanimous in concluding that blending hydrogen into natural gas is not perceived as suitable transportation alternative and the reuse of existing pipelines is generally preferred above the construction of new dedicated pipelines. However, whether reuse is preferred, depends on some aspects as argued below.

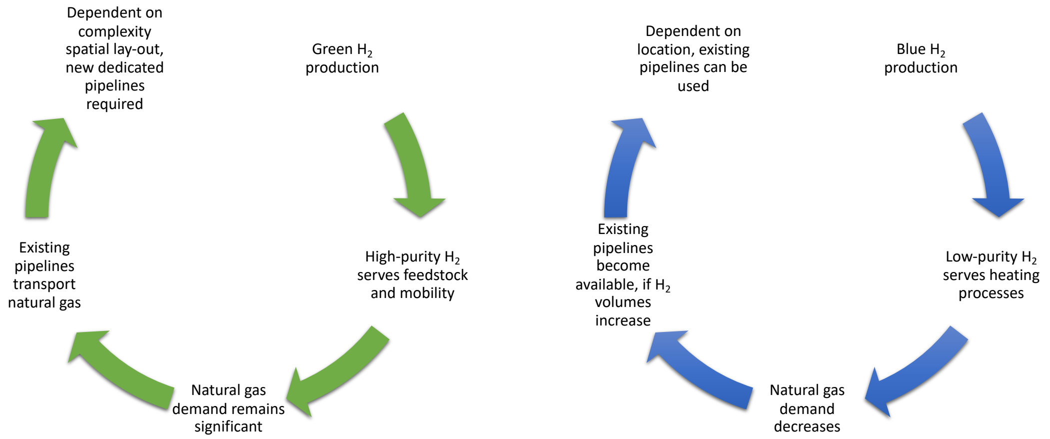

Figure 27: *Causal logic between hydrogen cycles and type of pipeline deployment.*

The location of existing pipelines should not determine the design of the pipeline network. The flow of supply and demand should determine the location and capacities of the required pipelines. Furthermore, the density of the required network in a sector dominate the decisions regarding the pipeline development. In industry, a few large pipelines with a limited number of connections are sufficient, where the built environment requires a finely meshed grid with millions of connections. Therefore, new dedicated pipelines in industry are a feasible alternative, while this is in general not the case for the built environment. These are perceived to be the determining aspects in deciding what type of pipeline is suitable.

The last determining aspect is whether there is still demand for natural gas at the desired location of the pipeline. In the industrial cluster, the natural gas demand is expected remain significant in the first transition phase. Therefore, new dedicated pipelines are required in any case. As the volumes of hydrogen become significant and, together with electrification, affect the demand for natural gas, possible influence could be observed on the type of pipeline design. Dependent on what transition strategy is used and whether the blue or green hydrogen cycle is mature, it would have the following causal relations.

To be concluded, three value chain level aspects can be defined critical in determining whether reuse of existing pipelines or construction of new dedicated pipelines is preferred:

- *The required location and capacity of the existing pipelines*, which should match the location and volumes of supply and demand flows.
- *Spatial complexity of required network in particular sector*, which determines the economic feasibility of new dedicated pipelines.
- *The natural gas demand*, which is influenced by the determined function and generated volumes of hydrogen.

4.5 Conclusions

The actor analysis of the current and future actor regimes showed the significant increase in multi-actor complexity. The future actor regime defines problem perceptions regarding the public vs private network, the sensitivity regarding public interference and control, the competition between sectors and the required high-level actor cooperation. The competition between actors is highly dominated by the industrial sector, as can be concluded from the actor regime dynamics and from the actor-influence diagram. Industry and network operators are strongly empowered and could gain advantage from this position in the transition period and are expected to obtain a leading role.

The power of industry follows from the identification of several factors, such as the strong urgency to decarbonize, sufficient investment power, the high expected volumes over a manageable number of actors with production and consumption centralized in a few clusters, and the fact that industrial actors control processes over the full width of the value chain. Contracts between industrial producers and consumers even further limit the possible influence of the other sectors in the early stage of the transition. Hydrogen is a chemically produced energetic product, where natural gas is a common resource, this underlies the difference in affairs between the two systems.

The public network operator is assigned the control over the network thanks to its supposed independent role and the open accessibility of an energy network infrastructure. However, the complexity in this regard arises from the observation that the public network operator has a significant stake in the design of the hydrogen value chain, meaning the continued existence of its enterprise after the natural gas flow is eliminated and the avoidance of sunk costs of the natural gas network infrastructure. This dynamic and the above stated argument that hydrogen is a chemical product and not a common resource, let the norms of the hydrogen value chain differ undeniably from those of the natural gas chain.

Although the industry and network operators are assigned both much power in the transition process, they exhibit opposing interests identified as controversies between entering and existing system actors. This tension in the future actor regime relates to the expected role of hydrogen in the energy system, the organization of the network, the type of pipeline alternative utilized, the market development approach and the role of the government and public enterprises in the transition. To enable an efficient transition and utilisation of existing knowledge and resources, the identified contradicting interests and perspectives between existing and entering system actors should be aligned.

The actor perspectives on visions and value chain set out the main focus for the construction of the end-visions and transition pathways. The purity of hydrogen is emphasized as determining factor in the future value chain, resulting in a differentiation between the green hydrogen and the blue hydrogen cycle. The fact that the various functionalities of hydrogen should be combined in one system increases the complexity significantly. This complexity causes a strong desire for long-term strategic planning and consistent policies to enable effective design in transition period for the end-vision

The impacts of the value chain on the type of pipeline in the network are not very strong, although a correlation between blue hydrogen and existing pipelines, and green hydrogen and dedicated pipelines is observed. However, this correlation depends on location and spatial complexity of the network. Furthermore, the condition should be met that sufficient hydrogen volumes are generated to have a significant impact on the natural gas demand.

The discussed contradicting perspectives and aspects causing tensions in the future actor regime, which are influencing the transition period, obtain a dominant role in the design of the transition pathways to the end-visions. The end-visions constructed in the next chapter are predominantly shaped by the actor perspectives on the value chain and visions level, and the outcomes of the systems analysis. Followingly, the end-visions should capture the aspects and complexities concluded in the previous two chapters that enable a constructive comparison, i.e. role of hydrogen in the system, the deployment of the green hydrogen or blue hydrogen cycle or both cycles, the international focus, large volume flows and multiple demand sectors with varying purity requirements.

Chapter 5

End-visions of 2050

Following the research framework, the end-visions designed in this chapter are concretizing the input from the actor perspectives on end-vision strategies defined in *chapter 4*. The end-visions constitute a strategic narrative and a quantified volumetric systems flow representing possible hydrogen systems in 2050. Three diverging end-visions are designed by the Energy Transition Model (ETM) using a diversified mix of technologies. In the three presented systems for 2050, the focus is on the volumetric flow, to maintain the focus on network infrastructure facilitating the flow between supply and demand. The quantification allows for a reliable comparison during the actor interviews between all three end-visions.

The input for the baselines of the end-visions is provided by scenario reports. Therefore, a selection of national reports is critically analysed first. The chapter discusses sub question 4:

What are, based on the actor perspectives, three viable end-visions for the hydrogen value chain in 2050?

5.1 Scenario reports

Scenario reports are bounding the design space for the hydrogen system in the Netherlands (Berenschot and Kalavasta, 2020). The focus is on national scenarios since elaborate regional scenarios, providing detailed hydrogen flows, are not available. Also, due to the connection to the national backbone and the transit function of Rotterdam, it would be inadequate to focus just on regional volumes.

Most of these reports focus on the transition towards a decarbonized energy system, with hydrogen as one of the elements. The more recent reports show a more prominent role of hydrogen in the future energy mix. These scenarios are assumed to be more relevant and to match with actual developments. In this section, the scenario reports that are used for the vision of the transition pathways are described and discussed on the contribution of hydrogen. The last section summarizes and compares the scenarios.

5.1.1 ‘Net van de Toekomst’ scenarios

The ‘Net van de Toekomst’ scenarios (NvdT) are presented in a report by CE Delft (CE Delft, 2017). The scenarios are modelled in the energy transition model (ETM) and aim for a CO2-reduction in 2050 of 100%. The scenarios focus on the energy system as a whole and make a division in end-use appliances based on: power and light, low-grade heat, high-grade heat and feedstock industry, passenger transport and freight transport. On the supply side the scenarios focus on renewable energy generation and conversion and storage. In this report, four scenarios are constructed:

1. 'Regie Regional'. In this scenario, the provinces and municipalities are in control and renewable energy is locally generated. This requires a strong utilization of hydrogen for flexibility and transport over longer distances. Conversion by electrolysers is decentral organized.
2. 'Regie National'. The government is in control in this scenario. There is a strong deployment of offshore wind with electrolysis at shore or even offshore. Large volumes of hydrogen storage are required.
3. 'International'. Netherlands is globally oriented and imports many different forms of renewable energy in this scenario. Hydrogen is connected to solar production in foreign countries. This causes domestic offshore wind and electrolyser capacities to be relatively underdeveloped.
4. ('Generieke sturing'). This scenario focusses on organic processes. The role of hydrogen is minimal, and this scenario is not determined to be relevant for further consideration.

The development of the industrial sector is based on the decarbonization pathways of the Port of Rotterdam by the Wuppertal Institute (Samadi et al., 2016). This required translation of these regional scenarios to a national scale, which coevolved with significant assumptions. Furthermore, the regional and national scenarios assume an energy self-sufficiency by the Netherlands. Since natural gas is neither extracted from the national gas fields nor being imported, there is no role for blue hydrogen in these scenarios. In the third scenario, almost all hydrogen is imported, and it is not specified what share of this hydrogen are produced by SMR with CCS or by electrolysis. In the NvdT scenarios, all hydrogen is produced from electricity overshoots and there are no dedicated renewable sources for hydrogen production.

5.1.2 'Integrale Infrastructuurverkenning 2030-2050' (II3050) scenarios

The climate neutral energy scenarios of II3050 are an update of the NvdT scenarios initiated by public enterprises, industry and network operators, to quantify the content of the climate agreement. As is the case with the NvdT scenarios, the II3050 present the boundaries of the design space in which possible futures can be sketched (Berenschot and Kalavasta, 2020). The next stage requires elaboration of the infrastructural transition paths related to the scenarios or prognoses in the playing field of these scenarios (Ministry of Economic Affairs and Climate Policy, 2020c).

In this context, the European CO2 scenario continues on the scenario 'generieke sturing' by NvdT. However, it is adjusted on many issues, and does describe a role for hydrogen in its energy system. Therefore, this scenario is included in the analysis. In the table underneath, the II3050 scenarios' most important strategic sectoral decisions regarding hydrogen are outlined.

In the industrial sector, hydrogen is deployed in all scenarios as heat and as feedstock. In this strategic choice there is no link obtained between the hydrogen production and utilization, and corresponding quality issues. Furthermore, the regional and national scenarios assume a future hydrogen system without import, which is highly unlikely following all strategy reports, policy statements and expert consultations.

The NvdT scenarios and Infrastructure Outlook Scenarios show the same values for installed capacities. IO2050 directly copied these values from NvdT, while II3050 updated these numbers according to, in their opinion, the increased focus on offshore wind combined with hydrogen.

	Regional	*National*	*European*	*International*
Built environment	-	-	20% hybrid H_2 heat pump	60% hybrid H_2 heat pump
Industry	-	Green H_2	Growth industry by blue H_2	Growth industry by hybridization with H_2 as backup
Mobility	15% freight	5% cars, 25% bus, 50% freight	30% cars, 30% bus, 25% freight	40% cars, 40% bus, 25% freight
Power sector	Green H_2 to cover peak demands	Green H_2 to cover peak demands	Hybridization in sectors, so low peak demand	Growth of power production covered with imported H_2
Production/ import	Green H_2 from solar and wind, no import	Green H_2 from solar and wind, no import	Mix of blue H_2, green H_2, and green H_2 import	Low green H_2 from solar and wind, high import

Table 5: *Hydrogen technologies input of II3050 scenarios*

Also, for regional and national scenarios the final demand of hydrogen is lower than in the NvdT scenarios, which is due to less utilization of hydrogen in the built environment. While in the European and international scenarios, the hydrogen demand is higher because of the role for hydrogen as feedstock in the growing industry, as fuel in mobility and in the built environment in hybrid heat pumps. For all scenarios, the final demand for energy carriers (both energetic and non-energetic) is lower compared to 2015. This can be assigned to the expected technological development and corresponding increase in efficiencies of appliances.

5.1.3 'Infrastructure Outlook' (IO2050) scenarios

The infrastructure outlook scenarios are constructed in a report of TenneT and Gasunie in 2019 (Gasunie and TenneT, 2019). These scenarios follow the quantification of the NvdT scenarios. The IO2050 scenarios focus on the infrastructure and demand, production is not included.

TenneT & Gasunie were able to identify three combined scenarios showing relevance for impacts on energy infrastructure and, specifically, the high-pressure transmission infrastructure:

1. High electrification and ambitious RES;
2. High gas demand and very ambitious RES;
3. High electrification and very ambitious RES expansion;

These scenarios are presented in a far elaborated interconnection with the energy infrastructure In Germany. Since they are developed in the integrated system expansion model, they provide useful insights in the combined utilization of gas, hydrogen and electricity. However, what is missing is the elaboration on the technologies of hydrogen, the strategic choices and infrastructural compositions on smaller scales. The focus is directly put on the cross-border infrastructure between the Netherlands and Germany, while the local development is not emphasized.

While observing the results related to hydrogen, the scenarios do not provide varying insights in demand sectors. The scenarios are not intriguing or innovative in this respect. This is shown in the graphs in *section 5.1.6*.

5.1.4 Berenschot 'Heat Pathway' scenario

Berenschot has developed three scenarios to contribute to pathways for the implementation of the Paris Agreement (Berenschot, 2018). The first two were extreme scenarios; electron scenario and a molecule scenario. These scenarios did not provide easily accessible data and were highly focused on one energy carrier. The third scenario of Berenschot, later developed, is the 'heat pathway scenario'. Here, there is more integration between the sectors presented. Therefore, this is the only scenario included in the research.

The limitation of this heat scenario, although it makes sense, is that hydrogen is only utilized as energetic product and not as non-energetic product. Although the hydrogen is only used as source for heat, there are no dependencies or consequences presented about relating the type of demand to types of production. Using hydrogen for heat requires less pure hydrogen than is being produced by electrolysis, so this would have been an interesting perspective. The production for hydrogen in this scenario is equally divided among blue hydrogen, green hydrogen and import. This presents a restricted view on the complexity and the multi-functionality of hydrogen.

5.1.5 'TKI Nieuw Gas' scenario

The last scenario report being considered is the report of TKI Nieuw Gas composed in 2018 (TKI Nieuw Gas, 2018). The scenario is constructed from the perspective of gas in the energy mix, where other scenarios first target electrification. The results show a significantly higher total energy demand, which could be assigned to the extraordinary expected growth of industry. Where some scenarios expected a decrease in total energy demand in industry, TKI assumes the just the industrial hydrogen demand already to be more than 22 times the current industrial hydrogen demand. The increase in energy, and hydrogen, demand requires the offshore wind energy capacity to be more than twice as large as in any other scenario and 160 times the current installed capacity; 160 GW. While the maximum potential of the Dutch part of the North Sea is estimated around 70 GW. Also, SMR with CCS is determined a promising role.

At the production side, this scenario divided itself into sub scenarios and presented the required capacities of green and blue hydrogen required if full demand is supplied by these energy carriers. This is unlikely, since the future energy mix is expected to have a diverse character. For the blue hydrogen scenario, the required storage CCS storage capacity is 128 million tons per year. The estimates for the Dutch storage capacity show 10 to 50 million tons annually for a period of 30 years (of Economic Affairs & Policy, 2019). This assumption would require CO2 storage abroad which is not very likely on the short term.

5.1.6 Comparison scenario reports

To allow for a constructive comparison the scenario reports, all volumes are processed in Excel and visualised in the figures below. In the tables in *appendix F*, the background data is presented. Detailed attention is paid to both the production and demand sides and the composition of these elements by different technologies. Since the TKI report is highly conflicting compared to the playing fields of the other scenarios, it is not included in these graphs. In the tables in the appendix, the graphs including TKI can be found. Also, the data of the scenarios used as background for these graphs is presented in tables in this appendix.

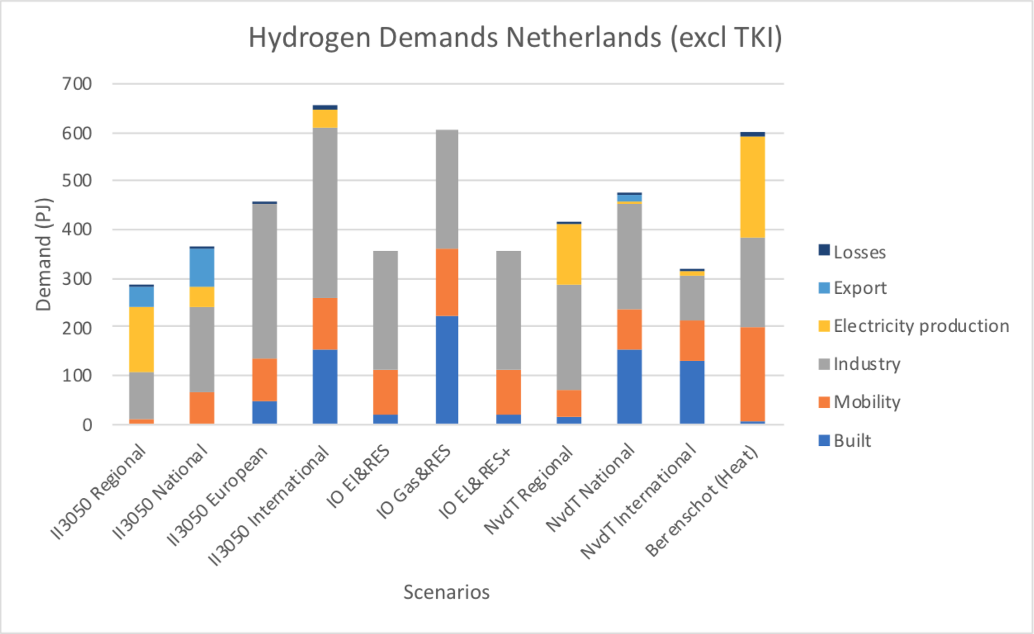

Figure 28: *The hydrogen demand volumes for the Netherlands as determined by the scenario reports.*

This quantified overview of the scenario reports shows by any means that the scenarios present extreme situations. Only some of the elements are combined in the scenarios, while the future energy system is typically a highly diversified mix of production technologies and demand applications. This cause the scenarios to be neither feasible nor viable representations.

The II3050 scenarios are an update on the NvdT scenarios and are composed three years later than the NvdT scenarios. Because of shifting policy perspectives in these years, II3050 shows the necessity for a more optimistic scenario in terms of hydrogen demand that is almost completely dependent on import. This clarifies the difference between the international scenarios of both reports.

The regional and national scenarios of both NvdT and II3050 assume the hydrogen demand to be fully supplied by domestic (green) hydrogen production and assume the Netherlands to be a hydrogen exporting country on a yearly base. This projected future is questionable due to spatial limitations for renewable energy generation in the Netherlands and the expected lower production costs of hydrogen in other countries. Another comparison between II3050 and NvdT to make note of, is the utilization of biomass in the NvdT scenarios and the absence of this resource in the II3050 scenarios. Although II3050 still determines a major role for biomass in the energy system, the utilization of biomass for hydrogen production is assumed to be too inefficient. Another lately experienced obstacle, is the increasing controversy on biomass due to the supposed damage to the rain forests the biomass industry is causing.

The IO scenarios of Gasunie & TenneT lack diversity in outcomes for the hydrogen system. Two out of three scenarios focus on electricity and renewables and are describing exactly the same role for hydrogen. The IO gas scenario tends more towards the international scenario of II3050 but ignores the role of hydrogen as flexibility instrument in the power sector. Most intriguing aspect of this scenario is the demand-driven approach that cause the production side

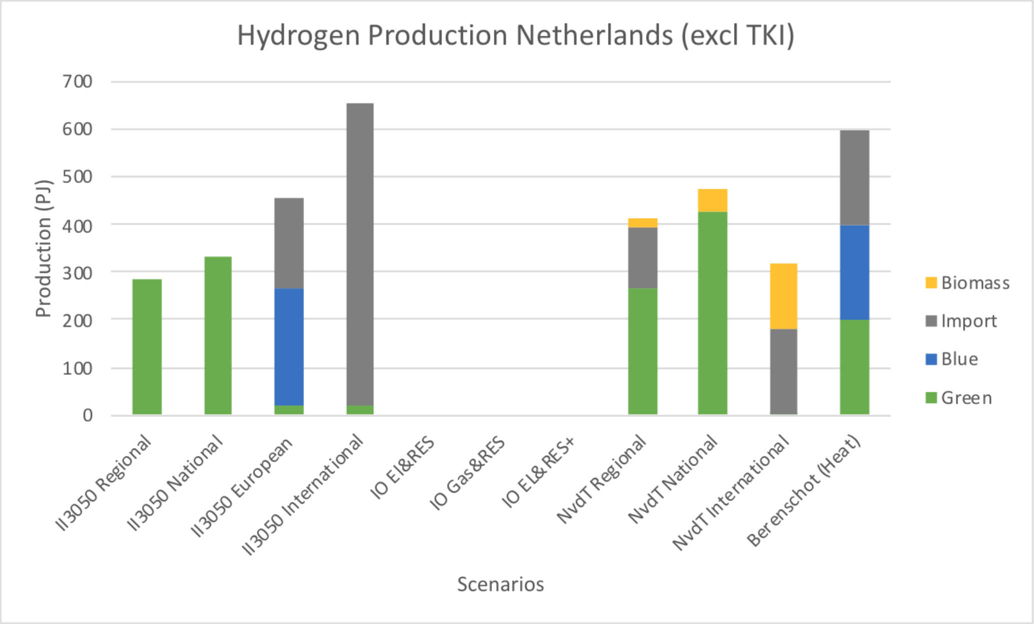

Figure 29: *The hydrogen production volumes for the Netherlandsfor each type of supply as determined by the scenario reports.*

to be simulated just to meet the demand. Therefore, no detailed information is presented on the demand side. This could be explained, by the interest of the network operators. However, in the development of the hydrogen supply chain, the emphasis should be on the interdependency of production, infrastructure and demand. Therefore, end-visions of this thesis will focus on all these elements and the IO scenarios are not suitable as base.

The Berenschot heat scenario is describing a very optimistic future for hydrogen as source for heat. The mobility sector was included to present consequences of the system affecting this sector. However, an in-depth analysis of the mobility sector was not performed. Both production and demand volumes are very equally divided over the different techniques/sectors in the scenario of Berenschot. This division obtains less relevant insights with respect to hydrogen related aspects in the scenario.

The paragraphs above presented remarks on the different scenario reports included in the overview. However, there are also some general remarks on the scenarios currently available in the reports. Almost all scenario reports follow a sectoral focussed approach, while for hydrogen it would be more interesting to create a more central role for the hydrogen flow that is matching production and demand. By focusing on the flow, the interdependency between the production and demand side is emphasized and the focus is set on the role of the network. As emphasized by the actor perspectives in the previous chapters, the different functions of hydrogen are key in the design of the future system. This is not accounted for in any of the discussed reports

All reports present scenarios for the energy system, considering hydrogen just as a component. This provides often not relevant or interesting outcomes to discuss the value chain dynamics and role of the network. In the first stages of the transition towards a hydrogen system, it would be interesting to focus on the hydrogen system while paying attention to the integration in the energy system. By focusing on the hydrogen system, a substantiated link between production and demand could be derived. Reading and analysing all the strategy reports and scenario reports,

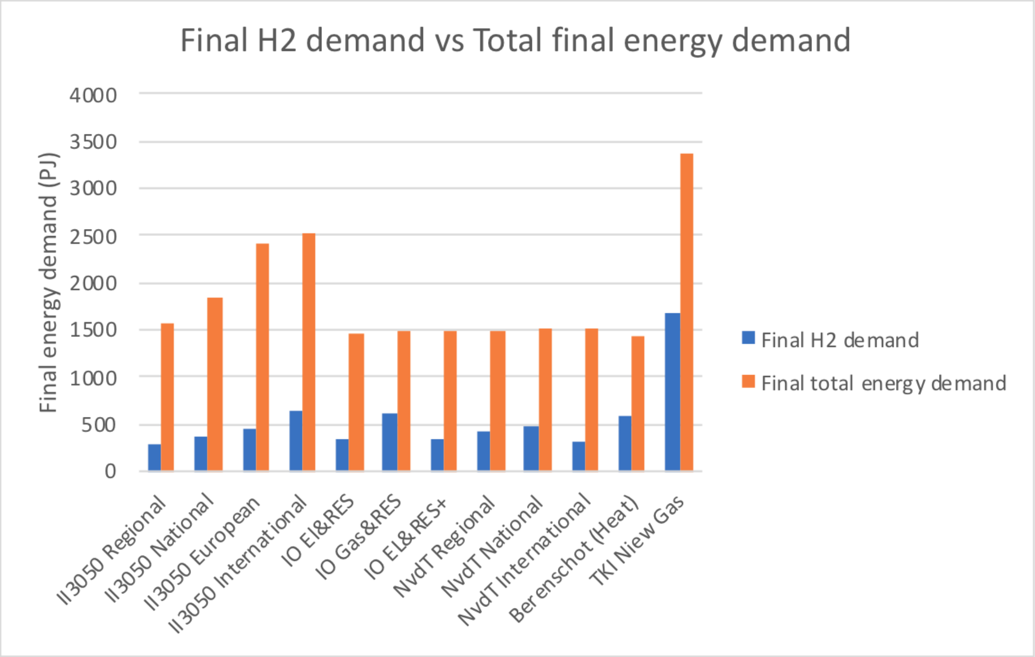

Figure 30: *The final hydrogen demand compared to the total final energy demand as determined by all research scenarios.*

both nationally and internationally, it is observed that the hydrogen supply should be preferably green in the future. However, this is limited by the offshore wind capacity of the Netherlands and the technological development of the Netherlands. Therefore, the vision that the hydrogen supply will be a reasonable mix of green, blue and import is more feasible. This is, however, in no scenario an applicable option.

From all discussed scenario reports, the II3050 scenarios present the most detailed description of the hydrogen system. The II3050 scenarios are sufficiently compatible with recent developments, present a diversified mix in demand applications and in volumes. Therefore, these scenarios are selected as fundament for the construction of end-visions for 2050. Multiple aspects should be improved in these scenarios to enable discussion of consequences for the value chain and network infrastructure. The regional, national and international scenarios will be adjusted by using the Energy Transition Model (ETM) to provide a solid quantified vision for the transition pathways. In the following sections, first ETM is introduced, after which the visions are presented.

5.2 Energy Transition Model (ETM)

The Energy Transition Model (ETM) is an independent, comprehensive and factual energy model that is currently being used by ministries, enterprises and NGOs, in the Netherlands and some other countries. The model is developed by Quintel and supported by, among others, Eneco, Berenschot, Gasunie, Steidin, GasTerra and TNO. The model is developed to improve understanding of the transition of the energy system. The transition can move in many different directions in which all options affect one another. Choices can be made on all options, including production technologies and demand applications. The ETM immediately shows the impact of the choices in graphs and tables. Both the II3050 and NvdT scenarios made use of the ETM. The ETM is a fully open source. Some shortcomings of the model restricted the outcomes or limited the in-depth analysis of the research in this thesis. These shortcomings will be addressed in the following sections while describing the visions for the transition visions. The openly accessible ETM files of the II3050 scenarios provided starting points for the end-visions.

5.3 End-visions for transition pathways

Three visions are constructed of which the relevance is based on strategy reports and expert consultation. During the actor interviews, the visions were presented and discussed with the interviewees after which necessary adjustments were made based on their expertise. The three visions are:

1. H2 - High purity;
2. H2 - Low purity;
3. H2 – Mixed;

The reason that the visions will be distinguished based on the purity of the hydrogen is that it represents the critical link between type of production and type of demand. This enables thorough assessment of the complexity of combining the green hydrogen, blue hydrogen cycle and international market, and their impact on the pipeline network later on in the transition pathways. The relevance of this complexity was concluded from the actor perspectives in *chapter 4*.

The type of production, by SMR or electrolysis, determines the purity of the hydrogen. With SMR, compounds of methane could still be present in the hydrogen, while with electrolysis, a very pure form of hydrogen can be produced. As explained earlier in the systems orientation, demand applications have varying requirements regarding the purity of the hydrogen. Utilization of hydrogen in fuel cells or feedstock requires the highest purity, while burning hydrogen for heating processes is possible with less pure hydrogen.

Although the pathways will present less extreme outcomes compared to the scenario reports. The outcomes will still differ in essential elements so that a reasonable analysis can be performed. It is decided to present more viable end-visions with a diversified supply mix to maintain security of supply. By presenting this diversity, the visions present combinations of the analysed research scenarios with influences of the reports in the table in *appendix C*. The table below shows what input was used for the visions:

	Vision 1: H_2 - High purity	*Vision 2: H_2 - Low purity*	*Vision 3: H_2 - Mixed*
Starting scenario	II3050 Regional	II3050 National	II3050 International
Secondary input	NvdT Regional Wuppertal pathways	Berenschot Heat II3050 European H-vision	TKI Nieuw Gas II3050 National Hychain-1

Table 6: *Scenario input for end-visions for 2050 of this research*

The general approach for constructing the visions by using ETM, was to start-off with a ‘starting scenario’ as outlined in *table 6*. The ETM-files of these starting scenarios are open available online. These starting scenarios were adjusted based on the actor perspectives on the end-vision strategy of the value chain. To make reliable quantified assumptions, in some cases it was necessary to make use of 'secondary input' scenario reports that elaborated in more detail on the particular value chain elements to be used in the specific vision. After the general outline of the visions was determined, corresponding hydrogen production methods and the level of deployment of hydrogen in the various demand sectors was determined. In the ETM, the aim is to balance supply and demand in a most efficient way, so by minimizing installed capacities and costs of the total energy system. To do so, flexibility technologies such as conversion and storage can be utilized additionally. Next to balancing supply and demand and maintain security of supply at all times, for this research the correlation between the type of production and the type of demand is a key element focused on while using the model.

5.3.1 General aspects end-vision strategy

From the actor perspectives, *section 4.4*, general aspects can be defined that should be discussed in the end-visions. A value chain consists of production, demand, network infrastructure, complementary value chain technologies and society. The deployment of production, demand, complementary value chain technologies and some societal aspects for the three end-visions of 2050 are analysed in the coming sections. The societal aspects are predominantly discussed in the transition issues and have been discussed in the actor network. The transition pathways elaborate further upon the network infrastructure, as well as the transition strategy. Following *section 4.4*, the analysis of the end-visions should discuss the following focal areas: the role and demand function of hydrogen, the deployment of technologies, the sectoral involvement, the flexibility functioning in the electricity system, the international character of national hydrogen system and the extent of total volume development.

5.3.2 Modelling assumptions

The limitations of the ETM and the limitations of this research project in general, regarding duration and scope of the project, require assumptions to be made in all stages. Some assumptions relate to specific installed capacities or demand sector specifications and will be presented in the separate sections for the pathways that follow hereafter. Other assumptions are made with respect to the system in general and will be discussed in this section. The general assumptions are divided in modelling decisions made, which relate to utilization of technologies or to strategy choices for the future system, and in assumptions necessary because of shortcomings of the ETM. In *table 7*, the assumptions are presented. The argumentation supporting the viability of the assumptions can be found in *appendix G*.

In the following sections, the end-visions' quantifications are discussed. Detailed background information, such as growth of sectors, costs of all resources and appliances, deployment of appliances, dependent and independent variables in the model etc., can be found in *Appendix H*.

Modelling decisions	Assumptions due to shortcomings ETM
Installed capacities for offshore wind and for electrolysis are developed interdependently	Installed capacities for electrolysers and H_2-to-power are set so that there are no hours without load
Green hydrogen is predetermined a prominent role	Hydrogen as fuel for shipping and aviation sector is not included
All visions exhibit a diversified hydrogen supply mix	The expected growth of industries towards 2050 is assumed to be similar to corresponding II3050 scenarios
Biomass gasification is not used for H2 production	Import and export only depends on net annually balance between supply and demand
Share of hydrogen in final energy demand is increased compared to scenario reports	Losses only refer to distribution losses, conversion losses are calculated in required installed capacity
Dedicated offshore wind farms directly linked to hydrogen production are included	The ETM reserves offshore wind capacity for aviation and shipping fuels, which should be considered regarding max potential of North Sea
All visions stay more or less within boundaries set by scenario reports	The total energy systems costs are calculated by ETM and the visions are constructed so that these stay within boundaries of the costs following the II3050 scenarios
All visions expect large development of offshore wind and electrolysers capacities	Detailed costs on utilization of hydrogen appliances is not given in ETM. Depends on high-level uncertainty
The maximum potential offshore wind capacity of the North Sea is around 60 GW	
Hydrogen is considered as feedstock in industry, also in Rotterdam	

Table 7: *Summarized modelling assumptions and decisions for the end-visions.*

5.3.3 End-vision 1: 'H_2 - High purity'

This end-vision is characterised by the principle that the main volume flow in the value chain is of high-purity hydrogen. This sets focus on the green hydrogen cycle. In the optimal case, high-purity hydrogen serves the automotive industry and the feedstock industry. As the required hydrogen is of high purity, the main production source is electrolysis from offshore wind production and from excess electricity from the grid.

To conclude what role hydrogen as a feedstock is able to play in the industry, the decarbonization pathways for the industrial cluster in Rotterdam of the Wuppertal Institute were studied. The II3050 scenario was used as starting point because of its high deployment of green hydrogen. However, elements of the NvdT regional scenario were reincorporated to include aspects as import and mobility demand. The flow of hydrogen in the system of vision 1 is presented in *figure 31*, where the green lines represent the flow of high-purity hydrogen and the blue line the flow of low-purity hydrogen (all values are for hydrogen, so the output of offshore wind and electricity is the value of hydrogen obtained by electrolysis from this resource).

As can be seen, there is no role for SMR with CCS in the end-situation of the vision. Since the hydrogen can be imported as liquid, bonded to other molecules or in gaseous state by pipeline, the imported hydrogen possibly requires conversion and/or PSA. During conversion, the purity of the hydrogen may possibly alter, and the purity of the imported hydrogen could be lower than the (almost) 100% purity required in the system. Therefore, PSA is a required element at that place in the system, although its deployment is minimized.

The demand is mainly dominated by Industrial feedstock, mobility and the power sector. This means that there is a large role for hydrogen as balance between supply and demand in the electricity sector as well. The role in the electricity system is also observed in the high input of excess electricity in the production of hydrogen. The dominance of electricity can be assigned to the fact that the hydrogen flow does provide heating appliances, so strong electrification is required.

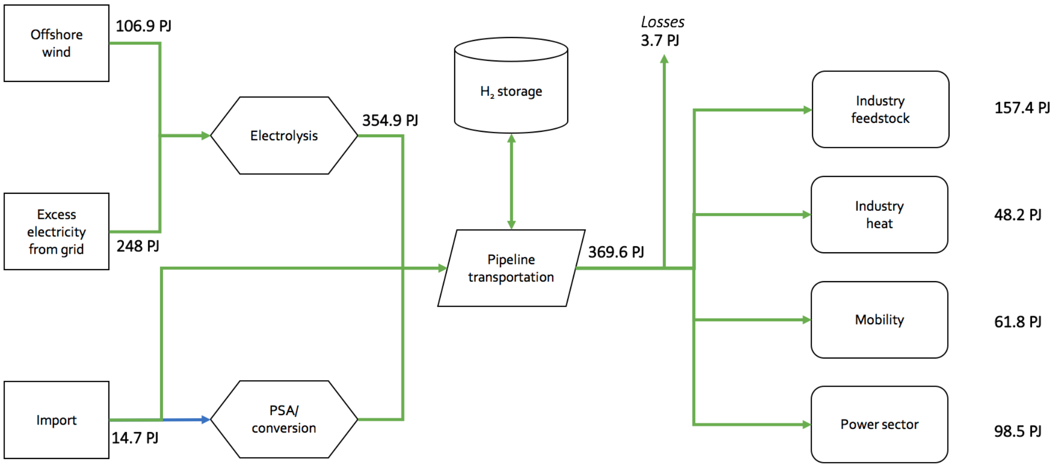

Figure 31: *Volume flow of end-vision 1.*

Not all demand sectors utilize high-purity hydrogen in their processes. This end-vision assumes high electrification of heating processes in industry by electrical boilers, but it is also assumed that not all high-grade heat can be provided in this way. Hence, there is a share of industrial heat in the final energy demand. Using high-purity hydrogen for heating implies the unnecessary utilization of high-purity hydrogen in processes where low-purity hydrogen would also had sufficed. Although it is a loss of quality, there are situations in which it is desired. Those situations relate to expected cost reduction for green hydrogen or just the consequence of the specific system standard.

The complexity in a network that is dominated by the production of green hydrogen, is that the renewable production source is volatile, while most demands are base load. This requires seasonal storage in salt caverns, definitely in the end situation when volumes become significant. On the demand side only the power sector demand is volatile. Since the majority of the demand is baseload, the required hydrogen storage capacity is relatively low. Yearly storage flow and other background information is presented in the *appendix I*.

5.3.4 End-vision 2: 'H_2 - Low purity'

This end-vision determines the regular flow in the value chain to be of low-purity hydrogen, which corresponds to the blue hydrogen cycle. Low-purity hydrogen exhibits also compounds of other gases, as carbon monoxide and methane. Because of the fewer purification steps required for the composition of hydrogen gas in this chain, the production process is expected to be cheaper when using SMR or ATR. Also, throughout the chain, there will be less stringent requirements for the quality of the volume flow, and thus less need for monitoring and less PSA after conversion. The flow of low-purity hydrogen causes the active role of SMR as production process for hydrogen in 2050. However, also electrolysis and import provide input in the system. Following the strategy reports, it is highly unlikely that there will be no electrolysis production in the future hydrogen system. The only aspect that can be questioned is to what extent electrolyser capacities will develop.

As starting point for the vision, the II3050 national scenario is used. The low-purity hydrogen will, in principle be used as source for heat and will function as a replacement for natural gas. Because of the role for blue hydrogen it is chosen to use the Berenschot heat scenario, II3050 European and H-vision report as secondary inputs for the vision. The background data can be found in *appendix J*.

The flow of hydrogen in the projected system corresponding to this end-vision is presented as follows (the green lines present the flow of high-purity hydrogen and the blue lines present the flow of low-purity hydrogen).

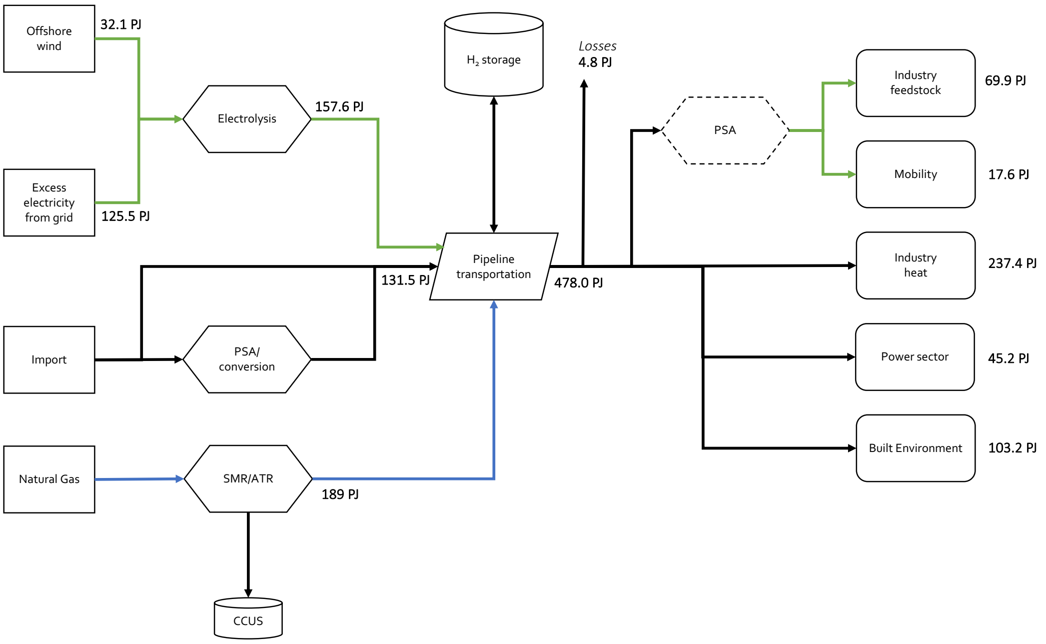

Figure 32: *Volume flow of end-vision 2.*

As expected, setting low-purity hydrogen as standard in the system enables the development of the markets where hydrogen is burned to generate heat. Since electrolysis capacity is assumed to be developed in any vision for 2050, there will be high-purity hydrogen as input, although in much smaller volumes than in vision 1. The high-purity hydrogen is blended in the low-purity hydrogen, which is an inefficient process.

Furthermore, it is assumed that some demand sectors utilize appliances for which hydrogen is the only decarbonized alternative for fossil fuels. This includes part of the heavy-duty transport, ammonia and chemical industry. These demand sectors require high-purity hydrogen. Therefore, purification by PSA at end-use site is a necessary additional step. The difference with PSA at the beginning of the chain is that, here, many small PSA units are required. In vision 1, the purification of hydrogen before transportation can be performed in a few large units. This could be favourable because of economies of scale.

The complexity in this system is the combination in the chain of high-purity and low-purity hydrogen. However, an advantage of blue hydrogen production from natural gas is that there is less need for storage than in the situation where green hydrogen predominates; blue hydrogen can be produced at baseload. However, when demand volumes increase, the volatility of the demand for heat in the built environment requires larger storage facilities since this demand has a peak during winter. This has been the case with natural gas for decades. So, in this case, the production is more baseload, but the demand is season dependent. Another advantage of the system could be that the 'other industry', which is the industry that is located in the built environment, can be supplied by hydrogen as well. Therefore, there is a significant role of hydrogen as an energy carrier thanks to the developed network in the rural and urban areas.

5.3.5 End-vision 3: 'H_2 – Mixed'

This vision expects development of production and demand of hydrogen along all possible alternatives. Therefore, it is the most complex vision since it combines the blue and green hydrogen cycle with a dominant role for the international cycle. Since the vision operates significant volumes of both high-purity and low-purity hydrogen, there is no decision made yet on the type of hydrogen set as system standard. The relevant considerations regarding the consequences of the system standard in this vision will be elaborated on in *chapter 7*. In industry, hydrogen is both widely used as feedstock and as decarbonized alternative for generation of process heat. Also, both the demand and mobility sector accepted hydrogen as supportive energy carrier next to electricity.

The vision is characterised by the highest hydrogen demand of all visions. The background on it can be found in *appendix K*. Therefore, a dominant role for import is undeniably required. The high import volumes specify the international character of this vision. As starting point for this vision, the II3050 international scenario is used. However, the hydrogen flow in the II3050 international scenario is almost completely supplied by import. As stated earlier, all visions assume development of production facilities in the Netherlands especially in the first years of the transition. The electrolysers built in these years are expected to be still operational in the year 2050. Whether the reforming units are still operational depends highly on strategic decisions by industry and on the cost price reduction of green hydrogen and hydrogen import.

The flow of hydrogen in the system of vision 3 is presented as follows (the black lines indicate the uncertain purity of the flow of hydrogen).

5.3.6 Shortcomings modelling in ETM

In the ETM, constructed visions can be scaled down to a specific region based on population or houses. For an industrial cluster, this would give a misleading representation since houses and population play a very limited role in an industrial cluster, although the energy demand is

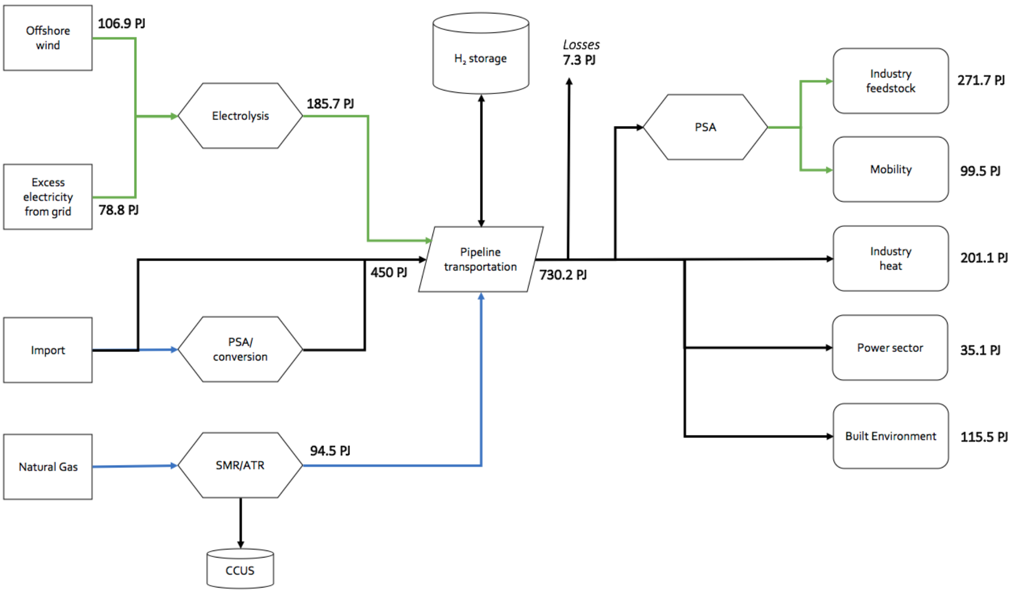

Figure 33: *Volume flow of end-vision 3.*

higher than in a rural area. A second alternative is to use the prepared Rotterdam-Moerdijk scenarios by II3050 to determine a conversion factor for all system elements. However, hydrogen as a feedstock is not included in the current demand. Since the future demand of appliances is determined in percentages of the current demand, this future demand will always be zero in the scenario when the current demand is zero. The industrial demand of feedstocks is often unknown for the 'klimaatmonitor', so this is often set to zero in ETM. Since the hydrogen as feedstock has a significant contribution to the future hydrogen demand, it is a major shortcoming of the tool.

So, scaling down the constructed national visions to the ICR will come with such unreliable assumptions, that it is determined not to fulfil this step. Moreover, since the PoR is expected to serve as transit port and the energy system has a (inter)national character, one could argue the necessity to describe the regional demands in such detail. For the research, and the construction of the transition pathways, the absence of regional quantification will not be a major barrier.

5.4 Conclusions

This chapter provides three possible end-visions constructed following the actor perspectives in *chapter 4* and the systems analysis in *chapter 3*. The fundaments analysed in these two chapters determined the necessity of the focus on the flow of hydrogen instead of the usually applied sectoral focus in scenarios. The perspective of flow recognizes the complexity of combining different hydrogen cycles, of green and blue hydrogen, in one system, complemented by the international hydrogen cycle. Inherently related to the flow of hydrogen is the purity of the flow that determines what demand sectors can be supplied most efficiently. The purity is defined as the key connection between the depicted supply and demand applications. All end-vision combine hydrogen flows from different production methods to multiple demand sectors with varying requirements for the product hydrogen. This design approach increases the complexity of the analysis, but enables to capture the full systems complexity and let this research to be unique compared to the supply chain studies discussed in *chapter 2*.

Therefore, the three end-visions constructed are: high-purity, low-purity and mixed purity. The high-purity end-vision is dominated by the green hydrogen cycle. This system exhibits the least complex structure since all demand sectors can utilize the same hydrogen purity and conversion steps and utilization of PSA is minimized. Downside of this situation is that high-purity hydrogen is utilized in end-use facilities where low-purity hydrogen would suffice. Hydrogen is mostly utilized as chemical product, serving the industrial feedstock and mobility sector, and as flexibility mechanism for the electricity system. Not focusing on the possible role of hydrogen as replacement of natural gas, increases the dependency on alternatives. Lastly, this end-vision exhibits the most national character. Therefore, the economic benefits of the Netherlands as transit country are minimal. The inability of benefiting from the economies of scale at the international market also limit the development of hydrogen volumes on a national scale. The Netherlands is not expected to be able to realize full upscaling in a nationally oriented market.

The second end-vision maintains a strong role for the blue hydrogen cycle. The hydrogen flow is mainly allocated to the industrial heat sector and the built environment, from which it can be concluded that hydrogen serves predominantly as replacement for natural gas. The formulation of the role of hydrogen in the system, causes a less stringent necessity for electrification of heating processes, and increases the direct application of hydrogen and electricity in end-use appliances. Therefore, the demand in the power sector and the supply of excess electricity from the grid is lower than in the first end-vision. The flow in the system corresponding to end-vision 2 gained in complexity compared to the flow in end-vision 1. The system operates three hydrogen cycles, i.e. green, blue and import. Since the purity standard is assumed to be low, PSA is mainly required at consumption site for the industrial feedstock and mobility. It enforced these two demand sectors to prioritize other decarbonized alternatives. The Dutch hydrogen system in this end-vision acquired a more international focus. This resulted in a larger volume flow, especially when the throughput flow of the Netherlands as transit country is also incorporated. The international import flow did not yet facilitate the phase out of blue hydrogen, which can be caused by multiple factors such as inadequate policy or not yet depreciated facilities. This will be further elaborated on in *chapter 7*.

The third end-vision is the most complex system since it represents the most diversity in origin and destination of the volume flow in the value chain and, thus, a deeply rooted combination of three hydrogen cycles. For this end-vision, it is yet unclear whether it is preferred to operate two purities at the same time in the network, one purity with the associated impact of conversion steps or whether a shift in standard is implemented as the transition moves on and value chain dynamics change. The strong international character of this end-vision incentivized the technological development, implementation of hydrogen appliances and, thus, the upscaling of volumes. However, it also increased the systems complexity significantly. The extent of the demand volumes require the blue hydrogen cycle to be still operational in 2050. Furthermore, as described in *chapter 3*, the Netherlands will be dependent upon import for the natural gas supply in 2050. Therefore, this end-vision strongly relies on the import of energy, of both hydrogen and natural gas. It is questionnable whether this is desired.

The end-visions differ significantly in the role of hydrogen in the system, the mix of technologies, the market development approach, the utilization of hydrogen as flexibility in the electricity sector, the extent of volume flow and the international character of the projected hydrogen system. This should enable a constructive comparison later on for three diverging transition pathways leading up to three end-visions with a strong variation of the core concepts mentioned above.

The following chapters will elaborate what issues are expected to be faced in the transition process towards the end-visions and what elements the possible transition pathways towards the end-visions should comprise. The focus of the end-visions on flow and purity in the value chain will enable the in-depth discussion on the complexity of the pipeline network design in the transition.

Chapter 6

Transition issues

In the development of a new energy system, such as the hydrogen value chain, several issues arise among varying fields of expertise. In *section 2.3.3*, some general systemic issues were identified from literature. These functioned as guidance during the interviews, after which the concretised issues for the value chain transition were identified.

The data derived during the interviews was clustered into five general value chain transition issues that present the outline of this chapter. Following the research framework, for all issues, corresponding challenges and actions are presented. In the final section, the actor-issues interrelationship is analysed. The comprehensive background analysis for the issues is provided in *appendix M*. In *chapter 7*, the issues are related to the pathway development and complemented by pathway-specific challenges and actions that together constitute the input for the transition pathways. The analysis of the transition issues with reference to the actor dynamics deals with sub question 5:

What are perceived issues to be faced in the transition to a pipeline network as part of the hydrogen value chain in 2050 and what are the key system actors empowered to deal with them?

The sections include a visualisation of the transition issues (encircled), the challenges (first level around circle) and proposed actions by the system actors (outer level).

6.1 Upscaling technology and volumes

Upscaling of technology and volumes is a strictly necessary requirement for the acceptability of hydrogen and the completion of the transition. Upscaling is believed to be the highest contributor to cost reduction of hydrogen, especially in production and distribution of the gas (2020b).

If upscaling of technology and volumes is not realized, there could be experienced negative consequences instead of the desired results. These consequences could refer to the lack of large-scale hydrogen deployment in general, which will determine the hydrogen transition to be a failed innovation, according to the theory of Geels (Geels & Schot, 2007). Another possible consequence, of less impact, could be that the national hydrogen market will remain immature, but that development at international scale is sufficient. In this case, the Netherlands will be fully dependent on imports from other countries and Rotterdam can still serve as transit port. The complexity in this prospect is the development of the infrastructure, which is dependent on

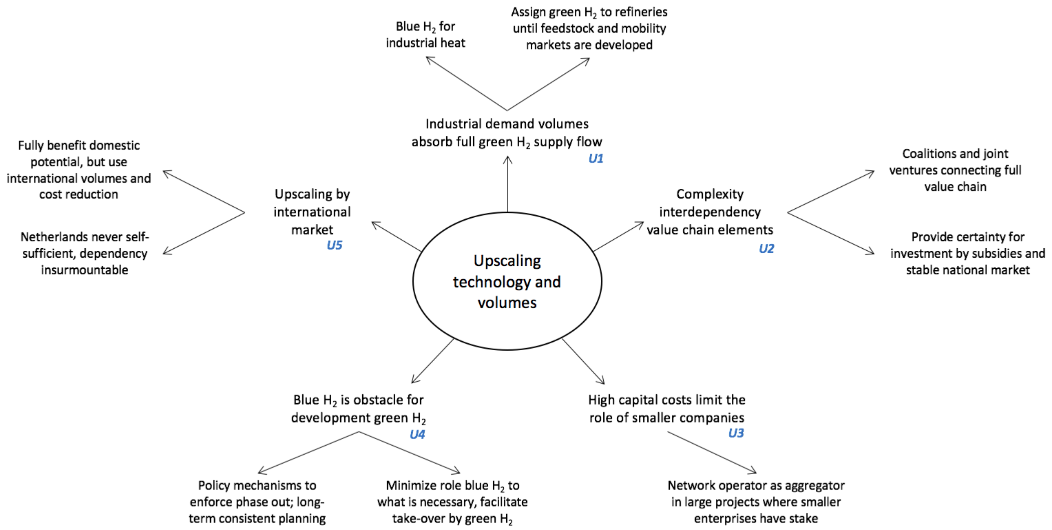

Figure 34: *Challenges and actions regarding upscaling of technology and volumes.*

the flow of hydrogen. If the flow of hydrogen is only provided by imports, which are expected to develop in the middle-term, the network infrastructure is expected to create scale at correlated period of time. The value chain is as weak as its weakest link, so if national production and demand volumes do not develop, the pipeline network will also lack required scale. So, although the Netherlands are likely to be highly dependent on import of hydrogen in the end-situation, the transition period requires domestic production to provide volumes while the international market is not yet developed.

6.2 Systems organization and standards

The system standards for the operation of the network and the organizational structure of the network are currently underemphasized as issue in the transition towards the hydrogen value chain, while they strongly affect the design of the future system. For these aspects, much contradiction is experienced between the existing and entering market actors. In *section 2.4*, four instruments were introduced to deal with monopolistic bottlenecks in a public network: price regulation, access regulation, separation and ownership regulation (Jaag & Trinkner, 2011). These instruments are included in many of the proposed actions and are considered while discussing the ownership of the pipeline network below, which is one of the main challenges.

Regarding system standards, two general aspects continuously dominated the problem perceptions of the interviewed actors regarding the future hydrogen transportation network:

- The purity (or quality) of the hydrogen in the system
- The private or public ownership of the network

Neither aspects experience clear consensus on their implementation among the various system actors. The public network operator is ensuring its position in the future system because of the phase out of natural gas and the still viable assets of public natural gas network that can be reused. Therefore, it is not remarkable that the public network receives major attention by

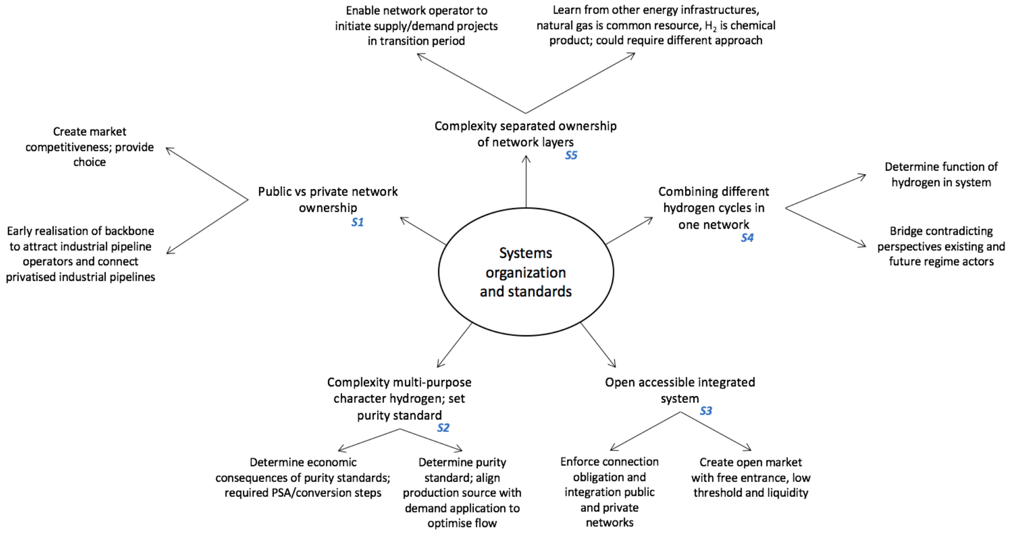

Figure 35: *Challenges and actions regarding systems organization and standards.*

political strategies. However, when looking from an independent perspective, it is not a foregone conclusion that the network operator is necessarily a public actor. When drawing comparisons between the electricity or natural gas network and the proposed hydrogen network, it seems logic. However, other (energy) networks in the Netherlands possess different organizational structures.

In the, often made, comparison with natural gas and its transition in the 60s in the Netherlands, two major differences are often neglected. First, natural gas is a common resource, while hydrogen is a chemical product. This observation desires different perspectives regarding deployment and ownership of hydrogen as gas and its assets in the end-situation. Second, the transition from city-gas to natural gas, because of the exploration of the Groningen gas fields, is often quoted in the discussion of the hydrogen transition. However, it should be noted that in the transition to natural gas, the market was not liberalized yet, so competitiveness did not exist (Cace & Zijlstra, 2003). Also, the government executed the production of natural gas, the construction of infrastructure, owned the molecular flow and guaranteed demand in all households. This is a major difference with the current perspective on the hydrogen transition, where the market is expected to fulfil the transition. The organization structure of natural gas, often referred to, is the end-situation of the natural gas network. When looking at the transition phase of the natural gas network, this shows a much different role for public enterprises and the government. Since, nowadays, the 'free market' is a constitutive aspect of the western market, one can also consider private companies to manage the role of network operator. By restricting their role in the network to the physical network, the division of ownership in network layers of a public infrastructure, following the framework of Jaag & Trinkner, is safeguarded (Jaag & Trinkner, 2011). Although, in this organization, the network is not publicly owned.

6.3 Policy and institutions

To facilitate and stimulate the development of the hydrogen value chain, policies and institutions should be adjusted or designed to facilitate this process. Where possible, the market is expected to overcome barriers by itself. However, in the design of new sustainable energy systems, in some situations, policy is required to increase technical and economic viability of decarbonized alternatives and to help the transition towards the next phase (Markard, 2018).

From the perceived challenges by the system actors as outlined above, it becomes clear that much focus is on the development of volumes for production and demand. Very little attention is paid in their strategies and visions towards the development of infrastructure. It could be that the infrastructure is in principal perceived to be a public responsibility from the perspective of the market actors, and that the government is expected to take care of it. Although governmental bodies are indeed intended to develop the infrastructure, this aspect is underemphasized and should be picked up by market actors as well. The most important factor, as clarified by the market actors, to ensure investment and success of the hydrogen transition, is consistent policy. Changing policies every few years together with change in power in the political system is disastrous for the trust that corporates need to experience to make long-term investments.

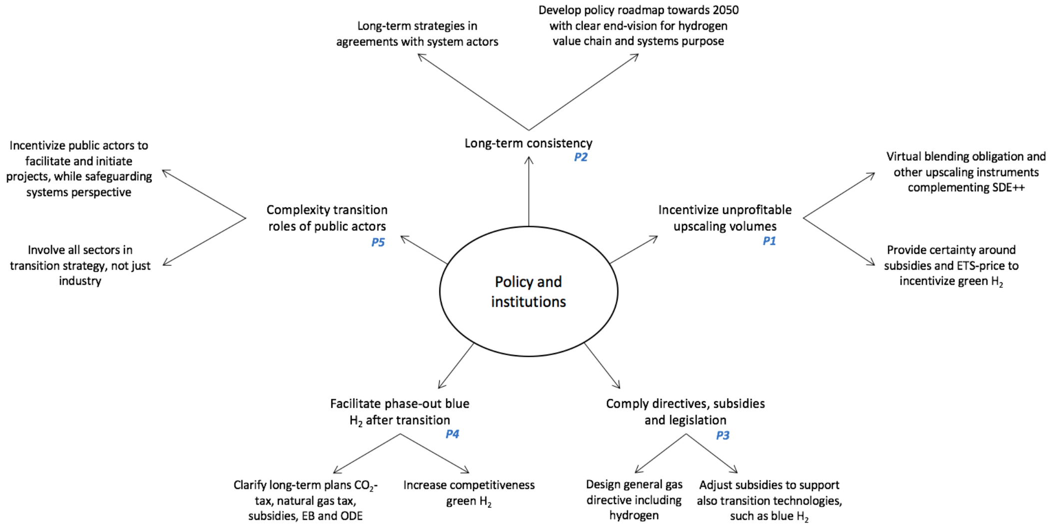

Figure 36: *Challenges and actions regarding policy and institutions.*

6.4 Economics

The challenges related to the issue of economics are either investment challenges or challenges related to the competitiveness of hydrogen and its system elements in the generic energy system.

Since the system actors do not provide full consensus over the role of blue hydrogen in the transition towards a sustainable hydrogen system, there is also contradiction regarding investment decisions and the role of blue hydrogen. The continuous repeating investment paradox is whether investments in other technologies are considered as not optimal since they do not directly support the 'real solution', which is green hydrogen. However, these investments are also expected to scale up infrastructure and demand volumes, which enforces in the middle- and long-term the business case for green hydrogen. Therefore, investing in transition means could be useful, but it should be clearly contributing to the desired end-situation. Investments in appliances and elements with the least impact on general functioning of the system are required so that the shift to green hydrogen is simplified in the future. Blending of hydrogen in natural gas pipelines does not fulfil this requirement due to complexity and costs for adjustment of end-use appliances.

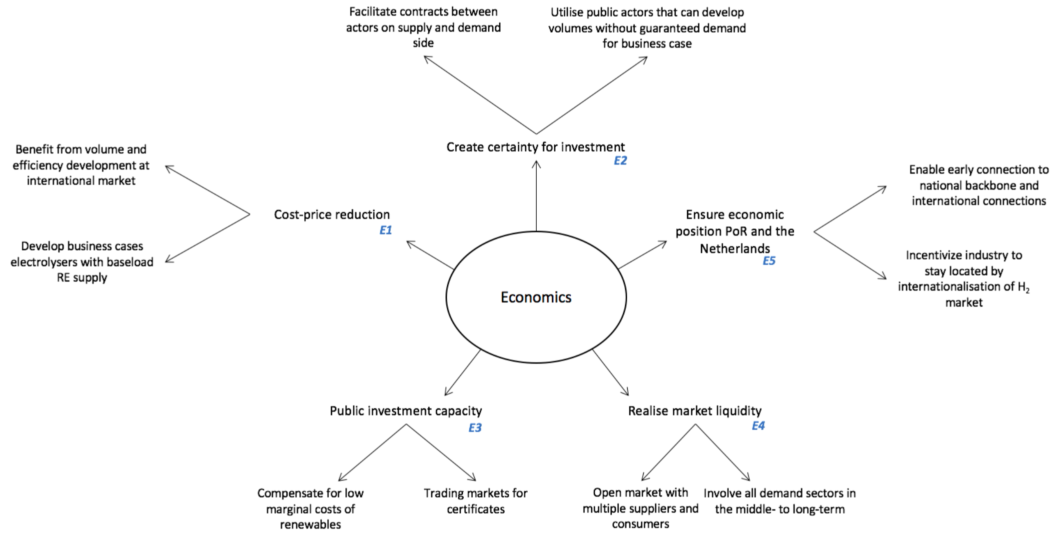

Figure 37: *Challenges and actions regarding economics.*

The first investment decisions are expected to be in industry since this sector exhibits large volumes with limited amount of connections. Although, the transition in industry is highly complex, the scale and elements are present to make it viable. Other sectors can benefit from investment and developments in industry but are not able to provide solid the investment base to facilitate the first phase of the transition.

For the economic position of the Netherlands and the PoR, it is of high importance that industry stays located in the port. For industry, it is economically attractive to be located near the source of energy. Since the Netherlands stop extracting natural gas, industry could be expected to investigate alternatives. Therefore, the Netherlands should feel the urgence to make the shift to hydrogen to incentivize industry to remain at its position. The pipeline infrastructure to supply the volumes is a crucial investment in this manner.

In the operation in a public hydrogen system, market pricing is an essential factor. An open network is required with clear tariffs. The existing privatized network could perceive this as threat but can also benefit from the opportunity to connect and utilize the liquidity of the public network.

6.5 Integration in the energy system

The hydrogen transition is part of the broader generic energy transition. The overall goal of this energy transition is to reduce CO2 emissions and to achieve a decarbonized energy system. The widespread utilization of hydrogen is expected to be able to contribute to this goal. However, the goal is not to use as much hydrogen as is possible if this goes at the expense of fossil resource consumption somewhere else in the chain. Therefore, the integration of the hydrogen value chain elements in the wider context of the energy system should be continuously monitored.

In the energy transition, three steps can be considered to decarbonize:

1. Reduction of energy use;

2. Electrification;
3. Complement with molecules (H_2) if needed;

After reduction, electrification is always the first alternative to be investigated, since electrons are required to produce molecules in this system. It depends on efficiency and economics whether there is electrified, or hydrogen is preferred. A major role of hydrogen considering integration in the energy system is as flexibility mechanism (conversion and storage) and as long-term transport alternative for the electricity sector. To be able to provide these functions, currently assigned to natural gas, enormous volumes are required. The capacity of infrastructure should be designed for these volumes. If the expectation is that these volumes are infeasible to achieve, due to unrealistic electrolyser capacities and renewable electricity generation, then the desired end-system is infeasible.

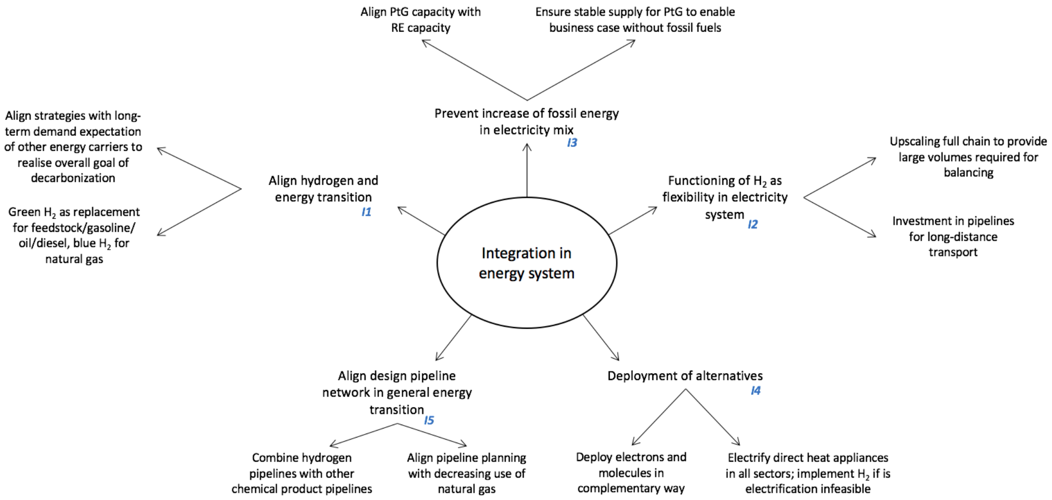

Figure 38: *Challenges and actions regarding integration in the energy system.*

In the future, there is a desire for a specific amount of energy at the moment of usage. If this energy is not directly supplied at the right time and storage is insufficient, problems are experienced. Therefore, it is required to observe efficiency from a systems perspective. Electricity, heat, hydrogen, natural gas and other chemical products should provide the combined solution by high-level interconnection of subsystems.

6.6 Actor-issues interrelationships

In the extended tables in the *appendix M*, one column summarized what actors had significant influence on the execution of possible actions to deal with the specific challenges. Followingly, this section elaborates upon the relation between the actors and the issues. *Figure 39* provides the schematic representation of the direction of the actors' power to significantly influence the process of dealing with the transition issues, in an actor-issue interrelationship diagram (Bryson, 2004). The many observed conflicting interests, because of the representation of different business incentives, hamper the design of the value chain.

As observed in the diagram, in the complexity to deal with the transition issues, there is a strong role determined for the governmental actors. They have significant influence on all issues

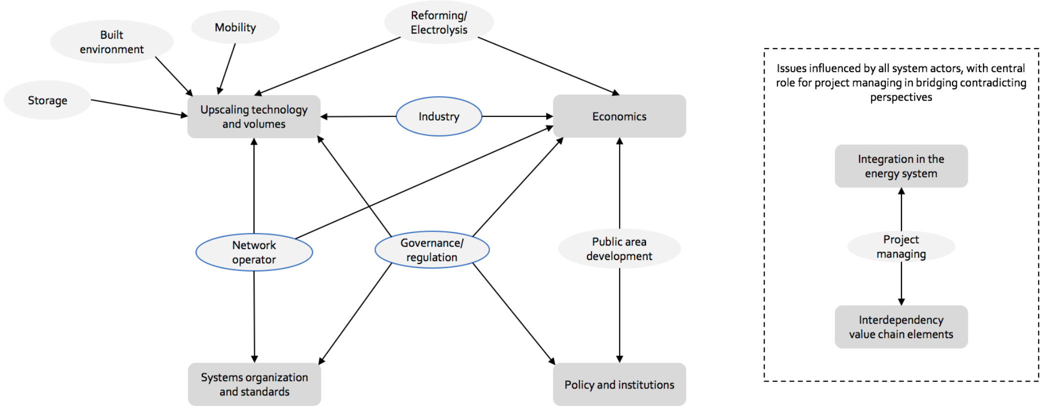

Figure 39: *Actor-issues interrelationship diagram, the two issues on the right are influenced by all system actors.*

since they determine the political strategy of a country and its regions and are involved in all agreements, upon which market actors base their strategies.

The public enterprise with the largest impact is the network operator, which is concerned with the task for distribution and transmission. The large influence of the network operator indicates the importance of the infrastructure in the ability of the hydrogen system to deal with the transition issues. The capacity of the infrastructure is essential for the system to enable the supply of the required volumes. The system actors acknowledge this perspective, which should be prioritized in future strategies and should be reflected in the near-term investment decisions.

Finally, it is to be observed that for actions related to development of scale and investments in the near term, the industrial sector exhibits strong power. Therefore, it can be concluded that it is inevitable that the first efforts in the transition, are to be expected in this sector. Subsequently, it will be of importance, and a responsibility for public actors, to facilitate that other, less powerful, market sectors can benefit in the middle- to long-term from the short-term hydrogen development in industry. The outlook of these routes will be further elaborated on in the next chapter.

6.7 Conclusions

From the actor perspectives on the transition period, five key issues could be determined: upscaling of technology and volumes, systems organization and standards, policy and institutions, economics and integration in the energy system. Initially, a sixth issue was observed, but this issue had already been discussed in the actor perspectives on the value chain in *section 4.4*; the complexity resulting from the interdependency of value chain elements.

This chapter provides a summarized presentation of the issues and the corresponding challenges and actions to deal with the issues. This conclusion will emphasize the most important findings for all issues to be incorporated in the transition pathways in the next chapter. The issue of upscaling of technology and volumes is to be overcome to enable cost reduction of hydrogen and thus its widespread acceptability and the completion of the hydrogen transition. The significant upscaling will be realized at the international market. However, since this market is expected to become mature in the middle- to long-term, the domestic market should be developed in the early phase-off to be aligned to the international network later on. Too early focus on internationalization can limit the investment in national production, which increases dependency and the risk insufficient network capacity.

The issue of systems organization and standards primarily refers to the operated purity and whether the future network is privately or publicly owned. The first aspect requires clarity in the very near-term to ensure technology specific investments and to enable dealing with the complexity of multiple hydrogen cycles in one system as outlined in the end-visions in *chapter 5*. The latter aspect is no foregone conclusion yet. In the discussion on ownership and operation of the network, comparisons are likely to be drawn to the natural gas transition and the operation of that network the past decades. However, hydrogen significantly differs from natural gas in several fundamental aspects, as discussed in this chapter. Other energy systems, as the water or heat network, or the chemical product pipelines have adopted a different organizational structure and could also serve as example. The private or public operation of the network could depend upon which demand sector is supplied or on what pipeline is used. One could imagine that the industrial sector would be able to construct their own pipelines and manage their own operation, but that regional and national backbones and the reuse of existing pipelines in the built environment are more suitable for public control.

The issue of policy and institutions' most important objective should be to guide the transition with minimum interference. However, clarity and certainty should be provided by long-term consistent policy to incentivize the market to invest. In the task to steer the hydrogen transition and to develop sufficient pace, the role of the government and public actors is an important but sensitive topic. They should facilitate and take away unprofitable peaks of niche technologies to create a market with liquidity, but minimize infringement with their own business interest. This collides with the stakes of the public network operator described in this chapter. The role of blue hydrogen as transition mechanism to pave the way for green hydrogen is experiencing the most discussion and is to be discussed in the transition pathways.

The economical issues of the future hydrogen value chain are majorly related to bringing down the production costs of hydrogen to increase its competitiveness in the market. This issue is strongly related to the issue of policy and institutions by its dependence upon subsidies. For the PoR in specific, ensuring its economic position as hub for international energy flows is the main goal of this hydrogen transition.

The transition to the hydrogen economy should be directly aligned with the energy transition in general, more specific the electrification of processes. Because of the important role of hydrogen as flexibility support, but also since the implementation of hydrogen technologies may not come at the expense of the renewable share of the average electricity mix. The goal of the hydrogen transition should be to reduce emissions, not to implement as much hydrogen as possible. Therefore, reduction of energy use and electrification should always be preferred, if more efficient, after which it can be complemented with hydrogen or another form of decarbonized molecules where possible.

In the execution of those actions, actors are inherently involved. The analysis of what actors are empowered to deal with the challenges, emphasizes a strong role for public actors. This may require a more active role of the government than currently performed, to push forward the transition. Also, the industrial sector exhibits a strong ability to deal with the issues. As some issues indicate, there is controverse experienced in the actor regime around the empowerment of industry. However, their ability to deal with the issues also justifies this empowerment. Therefore, in the transition period it is key to enable other sectors to benefit from the advantages obtained in the industrial sector. This requires active participation of the government.

The actions presented in the causal diagrams throughout the chapter are the main input for the actions selected for the transition pathways in *chapter 7*. In the tables in *appendix M*, the challenges and actions for all transition issues labelled on relevance to one or more of the end-visions.

Chapter 7

Transition pathways

Following the research framework, this chapter consists of four elements:

- General challenges and actions for all pathways that resulted from the transition issue analysis in *chapter 6*;
- The key pathway-specific challenges and actions required to fulfil the end-vision;
- The key actor dynamics and role for PoR;
- The lock-in effects;

The discussion on these elements provides the answer to the last sub question:

What are possible transition pathways, focussed on actions related to the pipeline network, towards the constituted end-visions for 2050 and what lock-in effects can be defined in the transition?

The three constructed transition pathways in this research all consist of two parts: a quantified end-vision and a strategic narrative of the route towards this end-situation. In this narrative, the focus is on the design of the pipeline network and the influence it has on the value chain development. Where *chapter 5* introduced the end-visions, this chapter will provide outlines of the most important challenges and actions constituting the route of the pathway. The challenges and actions resulting from all actor perspectives are analysed, according to the research framework, over three levels: visions, actor network and hydrogen value chain. To explore long-term effects of short-term actions and decisions, the pathways are divided over three periods of time, i.e. short-term, middle-term and long-term. The extensive visualisation is provided in *appendix N*.

First, the general challenges and actions for all pathways are discussed, which were provided by the transition issues analysis in *chapter 6*. With the input from the transition issues and from the actor perspectives of *section 4.4*, the pathway-specific challenges and actions are defined accompanied with a discussion on actor dynamics and the role of the PoR. The analysis on actor regime dynamics influencing the transition, in *section 4.3*, already identified the need for the pathways to deal with the empowerment of industry and public network operator and the contradicting perspectives on several aspects between existing and entering system actors. Furthermore, the actor perspectives on transition strategy outlined the specific interest in the role of blue hydrogen in the transition period. Each transition pathways deals with these issues in its own way. The chapter is concluded with the evaluation of the lock-in effects.

The timeline of the pathways heavily depends upon many external factors that determine the experienced pace of the transition. This pace is expected to change continuously as technologies develop, momentum may shift, investment power may disrupt or increase etc. Therefore, the outlined routes are no blueprint or strictly followed paths but should be read as roughly sketched future explorations, presenting systems dynamics influencing the role of pipeline transport. By aiming to present a comprehensive overview of the hydrogen value chain including production, storage, transportation, purification, conversion and demand elements, detailed perfection is not pursued. Moreover, the pathways provide an overview of strategic deliberations faced up to 2050.

7.1 General challenges and actions for all pathways

Underneath, the key aspects and actions are discussed that should be implemented in all pathways. They are, thus, contributing to all possible end-visions. The exact timing of implementation depends upon the desired end-vision and the determined transition strategy, but they can be roughly divided over the three periods of time accordingly. As observed, the majority of actions is situated in the short-term, which can be assigned to the general aim of the research framework to meet the challenge of describing the long-term system impacts and outlooks by near-term decision making and actor perspectives.

In general sense, all pathways aim for the same goal, which is the targeted zero-carbon economy. Hydrogen is perceived a dominant role in reaching this target but implementing as much hydrogen as possible is not a goal on itself. Foremost, the most efficient technology from a holistic point of view should receive priority. Policy mechanisms should safeguard this approach and should not incentivize consumption, but decarbonization, while deliberating short-, middle- and long-term factors.

7.1.1 Short-term

- Long-term energy transition policy

The lack of consistent energy policy is the most regularly pointed out bottleneck by all market actors to developing the required pace during the current transition phase. Changing political agendas and shifting public attention towards the (environmental) downsides of technologies, determine long-term agreements to be eliminated just a few years after implementation has started, which could cause a problem of trust for market actors. The absence of trust can have as consequence that long-term investments with high capital costs diminish and that companies move to other countries, which result in stagnation of the hydrogen transition in the Netherlands. Therefore, a long-term policy roadmap, preferably up to 2050, should be constructed to provide solid base for all innovative projects.

- Complexity transition roles of public actors

It should be debated what type of intervention is required by the government. As introduced in the previous chapter, there are major differences between the transition to natural gas roughly 50 years ago and the upcoming hydrogen transition. The network to be developed is not necessarily operated by a public network company and depends on many aspects. Also, either a partly privatised and partly public network could be one of the alternatives or a shift in ownership in the middle-term as the interconnectivity of the network increases. In all scenarios, the assets in the network experience separated ownership to prevent monopolistic bottlenecks and enable market pricing and free accessibility, following the theory in section 2.4. If this is not the case, government intervention is required.

- Comply directives and legislation

Currently, there exists a national gas directive in the Netherlands, based on European standards and norms. Hydrogen, however, is not included (Overheid, 2020). To enable implementation of hydrogen technologies and a volume flow through the system, a generic directive for the innovations should be constructed. The detailed interpretation should develop over the year to avoid restriction of innovations, but the regulatory recognition of hydrogen as energy carrier should be provided as soon as possible.

- Generate public investment capacity

Virtual blending, as currently is performed for biofuels, is perceived among all actors as easiest mechanism to scale up volumes and generate revenues for public investment. Virtual blending can be worked out as an obligatory system where a pre-determined amount of green hydrogen certificates is held, and trade of these certificates is facilitated (Scheelhaase, Maertens, & Grimme, 2019). It mandates hydrogen producers to implement a certain level of green hydrogen in their hydrogen flow, possibly compensated with certificates.

- Combining different hydrogen cycles

The contradicting perspectives of existing and entering system actors, as introduced in section 4.3.2, should be debated and brought together to be able to follow a consistent path supported by all system actors. Only if this succeed, the hydrogen system will be able to operate a homogeneous standard and system while effectively combining the different hydrogen cycles. If this does not succeed, the transition process will be inefficient due to investments in competing technologies.

- Complexity multi-purpose character hydrogen

The purity of the operated main flow of hydrogen in the system is important for decision system actors are intended to make for the specifications of other value chain elements. Whether the a high-purity or low-purity is operated depends on economics and systems efficiencies, but clarity is required in the short term.

- Complexity interdependency value chain elements

All system actors should cooperate, in joint ventures/coalitions/consortia, to enable interdependent upscaling of capacities and volumes of all value chain elements. However, in the first phase, specific decisiveness is expected by industrial sector and network operators since the actor analysis showed that the industrial sector is determined to be most applicable to enable upscaling and is prioritized by the network operators.

- Public vs private pipeline ownership

In the first phase, pipelines will be constructed only at crucial locations. In industrial clusters, due to significant natural gas demand, the role for reuse of existing natural gas pipelines will be limited. Therefore, new dedicated pipelines are the most viable option. Physical blending is not perceived to be a feasible alternative by any of the system actors. In the construction of the pipelines, overcapacity should be built to let the pipelines comply with future increasing demands. The pipeline capacities at crucial locations will incentivize and facilitate the upscaling of volumes in production and demand. Therefore, it is not necessarily negative if these pipelines are in private operation in the first period since they only serve industry. Longer term planning and incentivization by backbone realisation should convince involved industry to let the privatised pipeline evolve in the public network.

7.1.2 Middle-term

- Upscaling by international market

This aspect is introduced many times throughout the research. The Netherlands is not expected to develop significant volumes at the national hydrogen market to acquire a certain reduction in cost-price for hydrogen to become a competitive energy carrier. Therefore, profiting from the international market is required in the middle-term as volumes and capacities become significant. Furthermore, from an economic point of view for the PoR and the Netherlands, this international character is also desired.

- Realise market liquidity

In the middle- to long-term it will be a key priority to enable underdeveloped markets to benefit from cost-reduction and upscaling realised in the leading markets. To reach the other markets, a more active role of the government could be required.

- Realise market liquidity/Role of public actors

What markets are being developed first, depend upon available pipeline connections. Therefore, these should be planned in mutual consideration. In the middle-term, when the transition in the industrial clusters is under control and production volumes increase, the pipeline network can be expanded to enable development in other markets as well. As the interconnectivity and reachability of the pipeline network increases, the international connections should be integrated.

- Ensure economic position PoR and the Netherlands

For the Netherlands and the Port of Rotterdam, the internationalisation of the Dutch hydrogen market is key. However, this requires further complexity of the infrastructure. If national system standards differ, additional adjustment steps are required. This refers to both pipeline import and export at the borders with Belgium and Germany and the conversion and import terminals in the PoR.

7.1.3 Long-term

- Open accessible integrated system

At the point where volumes are developed sufficiently, the privatised and public network should be integrated and operated under centralised control. This interconnection is inevitable if full benefit from all advantages of the international market is desired and will facilitate the last phase of the transition period where the more complex sectors will also undergo the transition.

- Open accessible integrated system

The desired end-situation is a hydrogen value chain that is fully integrated in the energy system, where hydrogen serves as most important supplemental energy carrier for electricity. In this energy system, zero-carbon electrons and molecules complement each other.

The stepwise pathway for the general actions that are required for all pathways are visualised in the figure on the next page. Hereafter, the specific decisions and actions for the three research pathways are discussed. Where this section presented general logic, the following sections will be more specific in utilization of value chain elements.

7.2 Transition pathway for 'H_2 – High Purity'

The aim of this pathway is to explore a possible route towards an end-situation where there is a large-scale deployment of green hydrogen and blue hydrogen is completely phased out in 2050. The utilization of green hydrogen, which is demarcated by a high purity, allows for strong allocation of hydrogen to industrial feedstock and mobility demand. Also, a relatively strong role for hydrogen as flexibility mechanism in the electricity sector should be obtained.

7.2.1 Short-term

- Complexity interdependency value chain elements/certainty for investment

This requires a central facilitating role for public enterprises and a leading role for industry because of their investment capacity and presence in both supply and demand side. Consortia, joint ventures and coalitions can provide the required solid common business cases on which system actors can make their own investment decisions. This pathway is experiencing strong uncertainty levels on all elements of the value chain, even in the resource supply, i.e. renewable energy sources.

- Upscaling volumes electrolyser

The high-purity network standard is expected to stimulate the interest in electrolysis and limit the role of SMR, although stimulations are required. Alignment of renewable energy capacity and electrolyser capacity with network capacity to prevent unprofitable wind farms and electrolysers from curtailment or expensive capacity mechanisms regarding purchase agreements. Residual product flows can offer volumetric support since electrolyser production volumes will not be significant. Already planned SMR projects are initialized, but should be accompanied with centralised PSA, which dramatically increases production costs.

- Dedicated pipelines

Existing pipelines are still required for natural gas since hydrogen does not fulfil role as source for heat, so dedicated pipelines are preferred. Storage is required because of volatile production of electrolysers and the baseload demand of industry. However, the volumes are not significant enough yet for seasonal salt cavern storage and can be handled by performing linepacking in the pipelines.

7.2.2 Middle-term

- Hydrogen as flexibility in electricity system

Direct hydrogen demand is not experiencing extraordinary pace, but supply volumes start increasing, so regionally centralised H2-to-power facilities, the molecules are converted back to electrons, so long-distance transport is provided by hydrogen. Strong electrification of end-use appliances is required to provide a decarbonized heat alternative for natural gas. Decreasing electricity price due to larger share of renewables requires adjustments and design of new policy mechanisms to keep incentivizing investments.

- Mobility sector adopts hydrogen technologies

Electrolyser projects included already many actor groups. Now, the mobility sector starts adopting FCEVs for heavy-duty transport and profits from cost-price reductions and upscaling of volumes and infrastructure capacities of green hydrogen. The high-purity system standard is also in favour of the mobility sector. However, it is highly questionable if the mobility sector will be supplied by the pipeline network. Tube trailers are in general considered as more feasible alternative.

- Connection to national backbone

The network is starting to expand to enable international interconnectivity and connection to the national backbone for storage in salt caverns. Yellow hydrogen is imported by ships to the Port of Rotterdam or by pipeline through Spain and Italy. Both alternatives could be inserted in the high-purity national network, although the imported hydrogen by ships needs conversion and possible purification. Import is by any means required since the national potential to adhere with increasing demand volumes starts to run at its limits due to high electricity demand and spatial limitations for renewables. The network is now constituted of privately-operated industrial pipelines connected to publicly operated backbones.

7.2.3 Long-term

- Phase out blue H2

As the internationalisation of the market further develops, the lower cost prices of hydrogen imports cause a significant decrease in investments in domestic offshore wind farms and electrolysers. The contribution of import to the hydrogen supply mix also enables the phase out of SMR facilities that were still operating. Whether policy mechanisms are required depends on natural gas price, price of import and the price of green hydrogen from the national market. The next phase is to consider for the built environment whether it is favourable to make the shift to hydrogen for parts of the sector where decarbonization by other means did not succeed.

- High-purity hydrogen for heat

With the increase of import, the supply volumes are sufficient what causes a decrease in market price. This incentivizes industry to consider whether heating appliances can be adjusted to make the shift to high-purity hydrogen as well. Since the supply is sufficient, burning high-purity hydrogen for heating appliances is not considered as waste. The pipeline network with connections to the national backbone and international infrastructure is wide developed but can still be expanded if needed. Whether this is desired, depends upon the expected developments and decisions in the industrial sector and built environment as described above.

7.2.4 Discussion on pathway and actor dynamics

Since the focus in this transition pathway is on domestic green hydrogen production initially, the development of the international network infrastructure starts off relatively late in the transition process. It still provides sufficient volumes, also since the national demand is not developed to full extent. This could be a consequence of the difficulty of significant upscaling by green hydrogen due to the complexity of technological development of electrolysers. Demand volumes also developed slower due to exclusion of heating market in general in the short- and middle-term, which is assigned to be a market with high potential for hydrogen utilization.

The high-purity standard provides a clear norm for all network actors and does not provide difficulties regarding metering and billing different gaseous compositions. Also, for the specifications of end-use appliance this standard is easy to operate. However, it also constitutes a threshold for possible network connections and eliminates blue hydrogen as favoured alternative due to high costs of required purification steps. Therefore, the high-purity standard can also be observed as a bottleneck for the intended volume development.

The necessity for forming alliances to cooperate in the expensive electrolyser projects are not providing required pace in the first phase of the transition to enable upscaling of volumes at the start of the middle-term. Due to the late certainty about upscaling of volumes and centralised consumption at industry, the network operator also does not experience pressure to construct large pipeline capacities on the short-term.

The relatively late focus on developing connections to the international market and the low national volumes are restricting the PoR in its target to become the hydrogen hub for Europe. Although there is a flow for import and export, the volumes in this scenario are not expected to be sufficient to maintain the economic position of the PoR as it is nowadays.

Lastly, the built environment sector is not enabled to benefit from the hydrogen development in this scenario. Therefore, electrification of end-use appliances persists a strong role in this pathway.

7.3 Transition pathway for 'H_2 - Low purity'

The aim of this pathway is to explore a possible route where blue hydrogen is intensively used as transition mechanisms towards a decarbonized energy system with a dominant role for hydrogen. In this end-situation hydrogen is mainly used as energy source for heat in burning appliances in both industry and built environment.

7.3.1 Short-term

- Blue H_2 as transition mechanism

Subsidies, such as SDE++, should be made appropriate for SMR with CCS. Although, SMR is expected to have a better business case in the short-term than electrolysis, it still requires subsidies to be profitable. Large-scale SMR is expected to be operated since it simplifies CCS and possibly required PSA.

- Industrial pipelines

It is relatively easy for the industrial sector to manage their own business case for SMR facilities due to baseload resource production of natural gas and large sectoral demand of heat in industry. The transition power of the industry in this pathway and the investment in SMR facilities enforce the network operator to implement low-purity hydrogen as system standard. The pace in which SMR facilities are developed cannot be followed by the public network operator that is bounded to regulatory processes. The first dedicated pipelines in industry are privately operated. The low-purity network is not expected to infringe the business of the high-purity existing privatised network.

- Heat allocation

Mobilization decentral (investment) power of the built environment to start planning the logistics for adjustments end-use appliances and what areas will be prioritized first. Nationwide development is possible after connection of industrial pipelines, where production is located, to the national backbone. The planning of the built environment should be aligned in such way that it can benefit from the developed scale in industry in the first years.

7.3.2 Middle-term

- Reuse existing grid in built environment

As the built environment is ready to implement hydrogen gradually region by region, the network operator should plan connections to the regional and national backbone. The next phase is adjustment of existing natural gas pipelines. Although this operation is highly complex, the ongoing natural gas demand will not be a bottleneck.

- Connection privatised and public grid

Expansion of the public network incentivizes industrial companies to connect to public pipeline network to make use of liquidity. The public network provides more certainty and interconnectivity, which can be used for further upscaling of electrolysis capacities. Mutual agreement is desired upon the ownership and what actor is responsible for the new connected network.

- Green H_2 upscaling

Upscaling green hydrogen could experience difficulties because of investments being allocated to blue hydrogen and the low-purity standard, which causes the heating markets to develop first. Therefore, there is a lower incentive to scale up green hydrogen. Also, because of stable supply of blue hydrogen and efficient operation of CCS, there is less interest in the development of the international market, although natural gas is still imported. However, the direct utilization of hydrogen in the built environment enables a less dominant role for electrification and the resulting overshoot electricity is to be used in the upscaling of electrolysers.

7.3.3 Long-term

- International market

Policies are being implemented to stimulate the market to organize the gradual phase out of SMR and CCS. Increasing prices for blue hydrogen opens up the market for imported yellow hydrogen. Together with the upscaling of green hydrogen, the imported hydrogen causes a more increasing flow of high-purity hydrogen.

- Mobility and industrial feedstock

The high-purity demand sectors start to develop as the heating sectors are being supplied and the intended phase out of blue hydrogen has started. The complexity can be found in the supply of these sectors. The supply is either by the public network complemented with decentralised PSA at the end-location or by changing the purity standards in the network. The first alternative seems the most applicable in the situation since the volumes of green hydrogen in the end-situation are not significant enough to enforce this shift.

- Phase out blue H_2

Eventually, blue hydrogen should be phased out, but this pathway does not succeed in that before the end-situation. Phasing out blue hydrogen also requires the shift in the system standard from low purity to high-purity to directly supply the mobility and industrial feedstock sector without PSA at all end-sites. Direct utilization after import in the PoR or delivering mobility by tube trailers can prevent high costs for PSA units with a short lifetime since the shift is expected.

7.3.4 Discussion on pathway and actor dynamics

This pathway exhibits a major role at the start for the industrial sector that is not dependent on the public network operator since the first industrial dedicated pipelines are privately operated by joint ventures constructing them. This exhibits also the first challenge in this pathway, which is the large expected volume of industrial heat that is expected to attract all supply in the first years. This empowerment of industry that is facilitating its own supply increases the complexity for the built environment to receive necessary volumes. Since SMR is centrally operated in industrial clusters, it could require a pro-active role of the government or public enterprises to allocate volume flows to the built environment.

In the hydrogen system in this pathway, a separation is made between the privatised existing network and the privatised new network in industry. In the first network, hydrogen is operated as chemical product and in the second network hydrogen is perceived to be a heating source. The second network is in the middle-term connected to the adjusted natural gas pipelines to supply the built environment, where the first network remains privately operated. The two separate system are not expected to violate each other.

This transition pathway experiences a few major obstacles. First, the focus on blue hydrogen delays the transition to green hydrogen since the network standards are in the first periods designed to operate blue hydrogen as efficient as possible. Furthermore, the stable supply of blue hydrogen and the presence of significant volumes to scale up cause less desire to connect to the international hydrogen market. This is a loss for the economical position of the PoR and the Netherlands as a transit country. Furthermore, the low-purity standard is the most efficient in operation at the start-up phase. However, as interest and dynamics change and the shift towards a completely decarbonized system is desired, it becomes an obstacle.

7.4 Transition pathway for 'H_2 - Mixed'

The aim of this third pathway is to explore a possible route towards an end-situation where hydrogen is fully deployed on its wide-applicability. Where the other two pathways focused on either the implementation of green hydrogen or blue hydrogen in the short-term, this optimistic pathway pushes both technologies from the beginning to acquire a widely varied hydrogen value chain throughout the entire energy system.

7.4.1 Short-term

- Upscaling public network

Political and corporate strategies all aim to push the transition towards hydrogen directly. This incentivizes and creates the urgence for the public network operator to start upscaling the infrastructure with new dedicated pipelines to facilitate the transport of the expected large volumes. The common incentive to scale up as quick as possible derives mutual private and public investment in infrastructure. The industry is safeguarding its own pipelines, which are directly connected to the regional and national backbone. Scale can be derived by SMR in the first years, so the purity standard in the network is low and industrial heat is the first demand application.

- Deploying SMR and electrolysis

Scale can be derived by SMR in the first years, so the purity standard in the network is low and industrial heat is the first demand application. However, clear plans are constructed during start-off that in middle-term the shift is made to a high-purity standard to pave the way for green hydrogen and import. The early upscaling of the public network, strong policy mechanisms and early international focus determine the national production to innovate and invest in green hydrogen. The produced high-purity hydrogen is implemented in the low-purity network to contribute to development of scale. Since industrial heat is the demand sector, no PSA is required.

- Active internationalization

The pathway aims for a strong role of industry and the PoR as import harbour since this is the only end-situation where the overall energy consumption increases, and the growth of industry is highest (background in appendix H). Sufficient flows of hydrogen are needed to provide industry with an alternative for natural gas and maintain the geographical interested position. The common consensus is that the Netherlands will never be able to provide the promised and expected demand flows on its own, so quick internationalization is required. Also, the prospected upscaling of electrolysers is not reached without the benefits of scale from the international market.

7.4.2 Middle-term

- PoR as hydrogen hub

The active internationalization in the early transition phase, is resulting in the first contours of hydrogen import in the Netherlands and, more specific, in the PoR. Gaseous hydrogen is imported by pipelines and liquified hydrogen by ships directly to the PoR. Conversion terminals are required to enable further transportation in the network.

- Phase out blue H_2

The international contribution to the volumes, the upscaling of green hydrogen and the intended shift of a low-purity standard to a high-purity standard provide expectations for a started phase out of blue hydrogen. Although, the SMR facilities are not yet depreciated. Therefore, it is expected that a few will remain operational in combination with centralised PSA to run at peak demands. The government actively stimulates the phase out by taxing natural gas and quitting subsidies blue hydrogen and CCS.

- Built environment

The significant volumes and early connection to the backbones required seasonal storage. This enabled the focus to expand from industry to the built environment, the 2nd largest expected market. Green hydrogen is from the beginning also used as source of heat, following the target of obtaining significant volumetric scale. The built environment requires reuse of existing pipelines in connection to the dedicated backbones and industrial pipelines since production and import is all centralised.

7.4.3 Long-term

- Shift in purity standard

The widespread publicly operated network exhibits sufficient scale in high-purity volumes to enforce a shift from the low-purity to the high-purity standard. This has as consequence that parts of the built environment that were connected to the hydrogen network and industrial heat appliances all require adjustment to their appliances. However, the early developed long-term plans enabled the end-users to plan this transition thoughtfully. The shift in purity standard enables the mobility and industrial feedstock sectors to connect to the network.

- Strong developed role hydrogen

This pathway towards the end-situation develops the most pace in upscaling of volumes and quick internationalization. This enables a strong developed role for hydrogen in the end-situation. However, since the direct utilization of hydrogen in end-use appliances is high, there is a less decisive role of hydrogen as flexibility mechanism for the electricity sector. Therefore, it is assumed that battery storage can take over part of this role.

7.4.4 Discussion on pathway and actor dynamics

This pathway requires high-level cooperation from the beginning to immediately start developing the required pace. The other pathways focused very much on efficiency and economic optimization by designing the system in such way that high-purity hydrogen from electrolysers is linked to industrial feedstock and mobility and low-purity hydrogen from SMR is connected to heating demand with minimized conversion steps or 'loss of produced quality' throughout the system. This pathway immediately starts upscaling green hydrogen and insert the produced hydrogen in the public network operated at low-purity standard. This is a loss of efficiency and the expensive production process for green hydrogen. However, it contributes to developing the necessary scale.

The expected shift in system standard that is announced in the early phase of the transition could possibly cause a decrease in investment in SMR with CCS. The SMR facilities are essential in developing the required volume flows. Therefore, constructive agreements are needed between government and the market. Whereby, SMR producers are possibly incentivized by a guaranteed support for PSA when the shift is made to the high-purity standard or to be compensated when blue hydrogen is phased out.

The existing privatised hydrogen network will exhibit no urge to connect to the public network in the first years. However, as the high-purity standard is implemented and the organizational structure of the public network is sufficient, it may be interesting to connect these networks for both sides.

The main uncertainty of this pathway is the dependency on the international market. It is expected that the internationalization delivers cost-reduction and upscaling for electrolysers, but also liquidity to enable quick development of all markets. This perspective can exhibit major drawbacks related to technological and economical barriers regarding liquified import of hydrogen, political instabilities in other countries or the failing achievement of hydrogen demand development in Belgium and Germany. The consequence could be that the PoR does not obtain its role as hydrogen hub, the Netherlands loses its economic beneficial position, industrial manufacturers move to the source of energy in solar rich countries and presented end-situation will never be reached.

7.5 Lock-in effects of pipeline network on value chain

To enable a feasible hydrogen system, the design of the pathways is based on the ability to deal with the transition issues. The pathways show the dynamics in three varying routes. To assess the last component of the research framework, it is required to determine the lock-in effects. Lock-in effects are defined as the key aspects of the pipeline network, affected by short-term decisions, that are having influence on the long-term development of the value chain.

Therefore, first the key aspects affected by short-term decisions are determined by evaluating upon the role of the pipeline network in the three pathways. Subsequently, the lock-in effects are described by analysing the influence of these aspects on the development of the value chain.

7.5.1 Pipeline network in pathways

In *section 7.1 to 7.4* all actions of the pathway are discussed. In *table 8, 9, 10*, the actions for the pipeline network are briefly summarized and structured to enable the determination of five key aspects. These are further elaborated on in the description of the lock-in effects.

Time	**Aspects**	**Action**
Short-term	Operation/type/actor roles	Expand current H_2 network with new dedicated lines to utilise their existing flow
Short-term	Strategy	High-purity standard; H_2 as chemical product requires dependency of heat on natural gas so low availability existing pipelines
Short-term	Strategy	Line-packing in pipelines since electrolysers produce small volume flows
Middle-term	Capacity/outreach	Larger volumes of green hydrogen require connection to backbone and salt cavern storage
Middle-term	Ownership/operation/type	Privatised pipelines connected to public backbones requires decision on ownership and operation
Long-term	Capacity/outreach	Internationalisation of network boost volume flows
Long-term	Operation/outreach/type	Mobility infrastructure required. If by tube trailers, no action. If by pipelines, new dedicated required
Long-term	Operation/outreach/type	Larger volumes of international market enable high-purity H_2 use in industrial heat, use existing gas grid

Table 8: *Summary pipeline network related actions transition pathway end-vision 1.*

7.5.2 Lock-in effects

- Type of pipeline is situation dependent

Time	**Aspects**	**Action**
Short-term	Strategy	Low-purity; H_2 as heating source requires high deployment in industry
Short-term	Operation/type/ ownership/actor roles	Privatised new dedicated pipelines industry; public regional backbone; no connection existing network
Short-term	Outreach/type/ strategy/ownership	Plan adjustment natural gas network in built environment for market expansion of heat source; public ownership
Middle-term	Capacity/outreach/ strategy	Upscaling volumes by SMR; seasonal demand variations in built environment requires connection to national backbone and caverns
Middle-term	Strategy/operation/ outreach	Upscaling green hydrogen; no high-purity network; mixing high-purity in low-purity network or direct connection to mobility by tube trailers or to industry by point-to-point
Middle-term	Ownership/operation	Contracted agreements on connection privatised industrial lines and public pipelines; widely develop network connected to industry
Long-term	Strategy/standard	International market and upscaling green H_2 cause phase out of blue H2 and experienced difficulties regarding low-purity network standard

Table 9: *Summary pipeline network related actions transition pathway end-vision 2.*

Time	**Aspects**	**Action**
Short-term	Actor roles/type/ operation	Low-purity; H_2 as heating source; immediately deploy public network also in industry; mutual public/private investment
Short-term	Operation/type/ outreach	Dedicated public pipelines in industry with connection to backbones and storage; no connection to existing H_2 network
Short-term	Outreach/type/ strategy	Reuse existing grid in built environment; network expansion; market expansion
Middle-term	Capacity/outreach	Quick internationalisation requires sufficient capacities to enable volume flow
Middle-term	Strategy/operation	Implement transition of system standard from low-purity to high-purity
Long-term	Capacity/outreach	High-purity standard influence market expansion to industrial feedstock and mobility

Table 10: *Summary pipeline network related actions transition pathway end-vision 3.*

During the research, three pipeline transport alternatives were considered: blending hydrogen into the natural gas grid, the reuse of existing natural gas pipelines for hydrogen transport or new dedicated hydrogen pipelines. The actor perspectives on the type of transport and the value chain dynamics showed that reuse of existing pipelines is preferred, if feasible, and new dedicated pipelines are the alternative. The general consensus among all system actors is that blending significant amounts of hydrogen into natural gas is perceived as neither feasible nor desired. Followingly, the feasibility of the reuse of existing pipelines determines the outlook of the infrastructure.

Reuse of existing natural gas pipelines is not expected feasible in the early phase of the transition where demand is concentrated in the industrial sector. Therefore, in these situations dedicated pipelines are required for all pathways. The transition pathways show that industry is expected to construct these dedicated pipelines in the short-term.

Subsequently it depends upon the role of hydrogen, whether natural gas pipelines become available on a short notice or not. *(1)* If hydrogen is used as replacement for natural gas to supply industrial heat (low-purity hydrogen by SMR), the natural gas demand is expected to decrease in the public network and the chance for available pipelines increase. It should be noted that SMR still requires supply of natural gas, but this can be supplied by the national and regional backbones or by LNG directly to the SMR facilities in the PoR. *(2)* If hydrogen is operated as chemical product (high-purity hydrogen by electrolysis), natural gas demand is not expected to decrease in the public network since there will be no energy supply alternatives for heating appliances on a short-notice.

As industry is expected to start in the early phase of the transition with dedicated pipelines, the hydrogen transition in the built environment is dependent upon the possibility to reuse the existing natural gas grid. New dedicated pipelines could be implemented at crucial locations, but in the majority of the situations, existing pipelines will be used. Due to the dependence on sufficient supply volumes and the prioritization of the industrial sector, the transition in the built environment is expected at the earliest in the middle-term.

Concluding, the choice for the type of pipeline transport results from the utilization of other elements but is, on itself, no determining factor in the development of the hydrogen value chain. Reuse and new dedicated pipelines are both feasible alternatives and the one preferred depends for every specific situation.

- Network ownership and operation

As introduced throughout the report, the private or public operation of the pipelines is a contradicting debate between existing market actors and entering market actors. The origin of this contrast can be found in the fact that hydrogen is and industrially produced product but is by the entering market actors preferably deployed as common good; as replacement for natural gas. The transition pathways show that the private and public network can also be operated both, as interdependent networks or with an interconnection link for casualties and to increase efficiency. This interconnectivity can only be considered if the public network is operated with a high-purity standard.

The new dedicated pipelines constructed by the industrial sector in the early phase of the transition are intended to be operated privately. This will not hinder the public network operator since the regional and national backbone are always in public ownership. However, if the network is operated publicly from the start, market connectivity and the corresponding increase in volumes and cost-price reduction is earlier experienced. For the industrial privately-operated network, the public backbone will offer connections to other clusters, to large-scale storage facilities and to the international market on the longer run. After the private network is connected to the public backbone, it should be decided whether the ownership of the industrial private network will be taken over by the public network operator or if only the interconnection is facilitated. If existing natural gas pipelines are used, they are always operated by the public network operator.

The majority of the system actors and from a systems perspective, there is no preference regarding public or private operation of the network, as long as the network is accessible, and prices are determined by the market. Separated ownership of molecules and infrastructure is required.

- Network strategy in transition phase

The purity standard operated for main flow of hydrogen is determined by the general systems strategy that should be agreed by the systems actors, with a dominant decision role for the network operator. Clarity on the system standard provides certainty for business cases at both supply and demand side. So, although the network operator could also let its decision depend upon what flow of hydrogen is mostly utilized, the system actors should agree a general strategy to enable an effective transition. The following decision sequence for the general systems strategy is proposed:

1. What is the role hydrogen is predominantly expected to fulfil? Chemical product or heating source?;
2. What is the aim in first phases of the value chain development? Most efficient utilization, both energetically and economically, or quick upscaling of volumes?;
3. Determine technology for general upscaling method, green or blue hydrogen;
4. Determine systems purity standard;
5. Determine what demand sectors are most suitable to approach first;
6. Enable sufficient network capacity to start off transition; considering desired pace of upscaling;
7. Scale up production volumes towards provided capacity;

This proposed sequence is an iterative loop since it has to deal with the complexity of interdependence of supply, infrastructure and demand in the hydrogen value chain. This complexity can only be solved by high-level cooperation from the start and by bridging all contradicting perspectives between key actors.

Decisive regarding purity standard is the required level upscaling on the short-term. Green hydrogen can be inserted in a low-purity network *(Pathways 2 and 3)*, but blue hydrogen cannot be directly inserted in a high-purity network *(Pathway 1)*. As shown in the first pathway, a high-purity standard in the first phase limits the pace of upscaling of volumes. On the other hand, in the second and third pathway, the green hydrogen produced in the take-off of the hydrogen system is ‘wasted’ in the low-purity network. This decreases the economic and energetic efficiency of the network in the short-term since green hydrogen production has higher costs and more energy losses than blue hydrogen production. However, it should be argued whether this should be seen as a major problem in the first phase where the volumes are minimal. Therefore, upscaling is expected to be prioritized.

As the third transition pathway shows, if volumes are significant, the market is internationalized and conversion technologies are mature, a change in systems purity standard can be planned. This depends on desired end-situation, volumes of green hydrogen, whether phase-out of blue hydrogen is feasible and the economic consequences of changes in end-use appliances. Such a change should be planned way ahead since adjusting specifications of heaters in industry and built environment is a complex and expensive operation. Also, the business cases for SMR facilities and PSA units should be able to include this change.

A dynamic purity over the years, with an increasing share of hydrogen is not perceived feasible. The increasing level of uncertainty, the damage to end-use appliances and the different physical properties of natural gas and hydrogen cause too high risks and ineffectiveness. This is a similar discussion as whether blending is a feasible transportation alternative.

- Role network operator and industry

The key actors follow from the actor analysis techniques used throughout the research and can be easily observed in the visualised actor-influence diagram (*figure 25*), the actor-issues interrelationship diagram (*figure 39*) and subsequently their inclusion in the transition pathways. The general observation is that the key decisions are initialized by the network operator and the industry. Particularly in the short-term these actors determine the key actions in the value chain development.

The industrial sector is located at both production and demand side since hydrogen is originally an industrial product. Industrial corporates are involved in production projects by electrolysis and SMR and hydrogen can be utilized in refineries and in the (petro-)chemical industry. The fact that industry exhibits existing demand with limited connections for both high-purity and low-purity hydrogen and capital enforcement causes the strong empowerment allocated to the industrial sector by all actor perspectives on the development of the hydrogen value chain. The industry is in the current natural gas system directly connected to the public network operator, where other markets are connected to the regional networks. The existing strong link between industry and the network operator also clarifies the focus on industry, although the industry certainly exhibits favourable elements for the implementation of hydrogen.

The major drawback of this empowerment of network operator and industry is the unfair competition with respect to other actors. Therefore, the transition should be organized in such way that the other demand sectors can benefit from the industrial upscaling of hydrogen production and demand in the first phase. Problem in this sense, is that the network operator also has a stake, which is the continuing existence of its own business after the stopped extraction of natural gas in the Netherlands. The high expected demand volumes in industry could absorb all production capacity in the first phase. Therefore, the network operator should incentivize industry by providing connections to other demand sectors to utilize full market potential. If required, a pro-active role of the government could provide support.

- Pipeline capacity and outreach

This research puts focus on the role of the pipeline network in the development of the hydrogen value chain. Existing reports and literature often approach the system from a sectoral demand perspective. However, the infrastructure capacity determines the boundaries of feasible volumes and the expected location of supply and demand cause the need for an infrastructure. Therefore, this research aims to focus on the role of pipeline transport in facilitating this development of supply and demand and thus the development of the value chain. By putting the focus on the capacities of infrastructure, the obstacle of insufficient network capacity currently experienced in the upscaling of renewables in the electricity system can be prevented.

The realized capacity and outreach determine the level of volume upscaling and market connectivity. The connections to the national backbone with storage capacity, the international infrastructure and connections to the built environment sector are the factors that should incentivize expansion of the industrial pipeline network that is expected to be developed in the first phase of the transition.

The graph visually represents what important dimensions in the development of the hydrogen value chain are directly influenced by the key aspects of the pipeline network. This is a summary of the text in this section showing that only the type of pipeline has no influence on the outlook of the value chain but is affected by decisions made.

7.6 Conclusions

In this chapter, three pathways are constituted for the three determined end-visions earlier on. The end-visions recognized the complexity of the combination of the different hydrogen cycles in

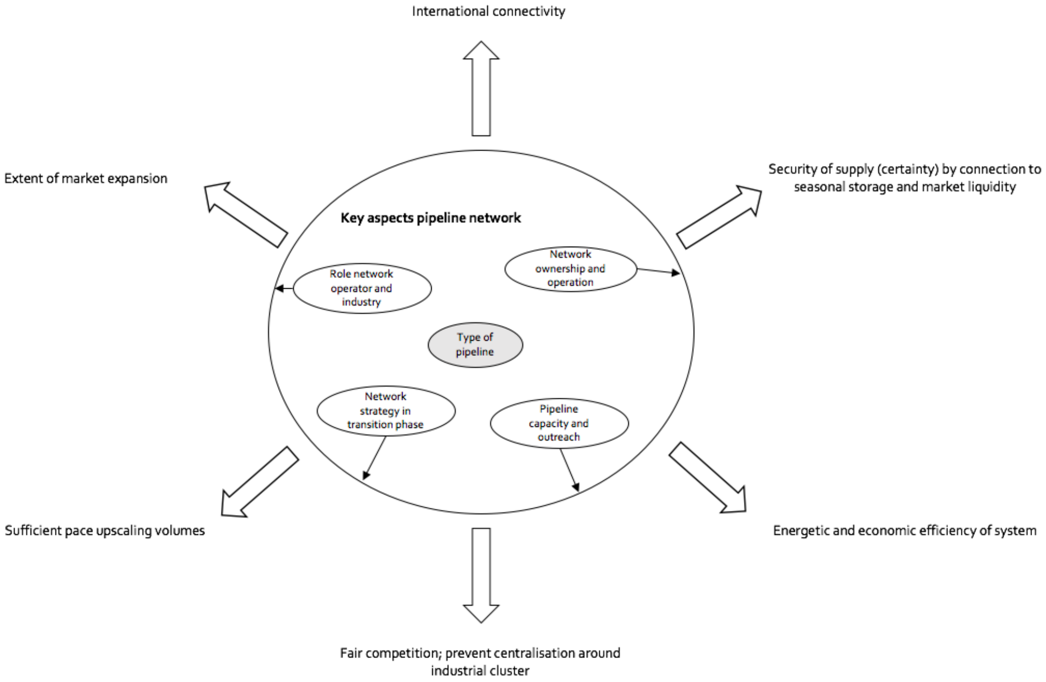

Figure 40: *Influence of key aspects of pipeline network on the development of the hydrogen value chain; the lock-in effects.*

one hydrogen system. Therefore, the end-visions were differentiated based on purity of the major flow of hydrogen in the system. In this chapter, it was explored what this complexity means for the development of the pipeline network and the influence on the value chain.

The 'high-purity pathway' shows a relatively late development of international network connections. The focus on green hydrogen and high-purity flow limits the upscaling of required volumes and inclusion of other markets. The restriction in development of volumes and inclusion of the built environment, limits the pipeline network to construction of dedicated pipelines in the industrial sector connected by the regional and national backbone. However, no widespread public network is developed. The late development of international connections limits the role of the PoR.

The 'low-purity pathway' explores a quick upscaling of volumes by the deployment of blue hydrogen with a utilization of hydrogen as source for heat. Although volumes increase, the deployment of green hydrogen delays. The competitiveness of blue hydrogen and investments in infrastructure for CCS decreases the need to connect to the international market and restricts the transit role of the PoR. As volumes increase, the dedicated industrial pipelines constructed in the early phase of the transition are connected to the public pipeline network supplying the built environment. This network enables the reuse of existing natural gas pipelines.

The 'mixed pathway' explores the most pace in the early phase of the transition by starting-off with a low-purity standard to benefit from the large volumes in the heat industry and utilize blue hydrogen as upscaling mechanism. This pathway accepts the utilization of green hydrogen as source for heat in the early phases at the expense of the loss of high-purity hydrogen. The major interconnections to the international market enable the required cost reductions for green hydrogen technologies and realize the phase out of blue hydrogen as import volumes increase, this results in the shift in system standard to high purity. The pipeline network evolved to facilitate the significant pace in upscaling of volumes and high interconnectivity to the international market, which should acquire the desired role of the PoR as hydrogen hub. The uncertainty in this pathway is caused by the dependency on the international market.

Generalizing the observations of the transition pathways related to the pipeline network identifies five key aspects causing the lock-in effects in the value chain development: type of pipeline, network ownership and operation, network strategy in transition phase, role network operator and industry, and pipeline capacity and outreach. These five aspects are expected to influence the long-term outcomes of the hydrogen value chain by having impact on the extent of market expansion, international connectivity, security of supply by connection to seasonal storage and market liquidity, the sufficient pace in upscaling of volumes, the fairness of competition and the energetic and economic efficiency of the system.

Chapter 8

Discussions, conclusion and recommendations

This research aimed to contribute to the pipeline development in the future hydrogen system by determining the strategic role of the pipeline network in the development of the hydrogen value chain. The literature study showed that many techno-economic and supply chain optimization studies considering the future hydrogen infrastructure exist, but that the socio-technical perspective, taking into account the actor complexity inherently related to this problem, is lacking. This resulted in the sub research questions that are answered in this chapter. Subsequently, there is reflected upon methods used and limitations of the research are discussed. The chapter is finalized by overall conclusion that answers the main research question and recommendations of this project for future research.

8.1 Discussion sub questions

8.1.1 Research framework

The research framework combines multiple levels as approach. The aim is to explore long-term effects by near-term decisions and actions. The desire to apply as much as a systems perspective as possible, could have come at the expense of simplifications or generalisations at deeper levels of analysis. It is believed that in this phase of the hydrogen transition process, as introduced in *chapter 2*, the research area has more interest by a constructive outline of strategic decisions and issues to be faced regarding the general role of the pipeline network in the value chain, than by a detailed optimalisation of a bundle of elements. The chosen approach increased the complexity of the strategy problem significantly but enabled the identification of constructive challenges and dynamics at the systems level. Complementing the basic three-level framework of Hughes by systems analysis, actor network theory, systems transition issues and transition pathway theory provided the tools to fulfil the aim of the research.

However, this highly qualitative research framework certainly comes with limitations. As said, applying a systems perspective causes simplifications and generalisations at a deeper level of analysis for all levels in the framework. A detailed technical or economic analysis of the value chain and its elements is not provided. Although these analyses, especially for a projected long-term process, up to 2050, are generally abundant in assumptions and uncertainties, they can increase the ease for validation of results. The focus on the pipeline network determined to include only directly connected value chain elements in the analysis, which provides insights on direct impacts but a limited view on indirect effects.

The framework constitutes as core element the actor network and determined long-term effects on visions and value chain by the characterization of current dynamics in the actor network regimes. The impacts of the visions and value chain on the actor network over the transition period is not assessed to a full extent due to time restrictions of the research. More interviews or participatory workshops would have been desired to assess the impacts on and dynamics in the actor network as well. This limitation restricts the dynamics in the analysis of the research. It should be noted that such an extension of the research would require openness by system actors on their business strategies, which is hard to obtain.

8.1.2 Systems analysis

The systems analysis defined the current situation of the hydrogen system in the Netherlands, presenting the outlook of the existing industrial privately-operated hydrogen network between Rotterdam, Belgium and North-France. The existing private market operates hydrogen as a chemical by-product in the production of chemical processes or is directly used after on-site small-scale reforming. The systems analysis shows that in the future public system, hydrogen is the main product flow and could function as heat source, feedstock or fuel. Combining these two markets introduces and increased level systems complexity due to differing physical properties of hydrogen and natural gas.

In volume flows, the existing and expected future market are incomparable. The dramatical increase of hydrogen demand and the limited capacity of the North Sea shows that net import of hydrogen on a yearly base is inevitable in the Netherlands. The exploration of different demand sectors also shows that hydrogen can fulfil two separate roles and that two separate systems are generally designed.

The two different roles hydrogen can fulfil in the future system and the relation of this role to the purity of hydrogen, to the type of production and to the demand sectors is analysed. This determined a key role for PSA as technology able to provide a volume flow between the two possible systems (between green and blue). The derived knowledge on the relevant value chain elements, related to production, transportation, consumption, conversion, purification and storage enables the researcher to assess the actor perspectives. Analysing the projects in the ICR and the Netherlands shows the complexity experienced in integrating the two separate cycles of green and blue hydrogen. Green hydrogen experiences the momentum, but the urge for blue hydrogen is not clearly observed.

8.1.3 Actor network and perspectives on visions and value chain

The contradicting perspectives of existing versus entering system actors deliver insights in interesting focus on strategic elements; the role of hydrogen in the energy system, network organization, type of pipeline, market development approach and the role of the government in the energy transition. To fulfil the hydrogen transition, the contradicting views upon these elements should be bridged. These are elements attacked in the transition issues and in the transition pathways. Not only between entering and existing actors contradicting perceptions are experienced. The large variation in business incentives among all actors complexifies the design process.

The dynamic of actor roles in transition period and end-situation shows the most empowerment at the industrial sector, which is also the producer of hydrogen by electrolysis and reforming, and the network operator. The actor perspectives show no clear preference for the type of pipeline in the value chain. The only incentive is an economical preference for reuse of existing pipeline where possible. The strong role for industry is assigned to: the urgency to decarbonize and the suitability of hydrogen for several elements in industrial sector, the involvement of industry as competitor on both supply and demand side, sufficient capital power, centralisation of production and demand in an industrial cluster, and the high expected demand volumes over a manageable number of actors. The empowerment of industry and the network operator determine largely the outcomes of the next chapters.

The actor perspectives provide benefits and bottlenecks in the future system, and the role in transition period and end-situation for all value chain elements. Subsequently, the relation of all elements to other value chain elements, to energy system elements and to pipeline transportation in particular is structured from the perspectives of actors on their part of the value chain. These overviews provide the fundament for the construction of the transition pathways and the interpretation of the transition issues.

8.1.4 End-visions

Three possible end-situations of the hydrogen system are visualized and quantified with use of the Energy Transition Model (ETM). As base for the three visions the regional, national and international scenarios of the II3050 scenarios are chosen and complemented by other scenario reports. Choosing these reliable sources as fundament for the three visions avoids the necessity for this research to make assumptions related to the energy system in general, which saves time on the limited timescale of this project. The three visions are summarized below:

- Visions 1: H_2 – High purity

The majority of supply in this vision is provided by green hydrogen supported by import. Therefore, this vision requires full potential of domestic renewable energy sources; offshore wind in particular. The total energy demand is expected to decrease compared to 2015 and the overall hydrogen demand is relatively low. The dominant demand sector is industrial feedstock, but hydrogen is also strongly utilized as flexibility in the electricity system. Smaller volumes are allocated to the mobility sector and industrial heat.

- Vision 2: H_2 – Low purity

In this vision, there is a strong role for blue hydrogen in the supply mix. Although, green hydrogen is less scaled up than in the first vision, the volume flow from electrolysers is significant. The lower utilization of domestic sources requires a more dominant role for net import of hydrogen. The total energy demand is expected to decrease compared to 2015 and the hydrogen demand is relatively moderate. In this vision, most volumes are allocated to industrial heat and the built environment. The use of hydrogen as feedstock, as flexibility in the electricity system and as fuel in mobility is limited.

- Vision 3: H_2 – Mixed purity

This last vision is predominated by imported hydrogen and, thus, the dependency on international market. Following the project timeline in *appendix C*, it is can be expected that green hydrogen serves the system in any future situation, so also in this vision. The relatively very high hydrogen demand in this vision also enforces an active role of blue hydrogen. The high demand results from the stronger expected growth of demand sectors; it is the only vision where the total energy demand is expected to increase compared to 2015. The allocated demand volumes are widespread over all demand sectors. Only the role of hydrogen as flexibility mechanism for electricity is limited.

All visions exhibit a significant role for green hydrogen and are supported by import since *chapter 3* concluded that self-sufficiency of the Netherlands is expected to be infeasible. The role of blue hydrogen in 2050 depends on its utilization as transition mean for upscaling of green hydrogen. The end-visions are complemented by the actions described in the transition pathways.

8.1.5 Transition issues

The actor interviews identified six relevant transition issues from a systems perspective that the hydrogen value chain experiences in its development; all issues constitute many challenges and actions to deal with:

- Upscaling of technology and volumes;
- Systems organization and standards;
- Policy and institutions;
- Economics;
- Integration in the energy system;
- Interdependency value chain elements;

The interdependency of value chain elements was elaborately discussed in the actor perspectives in *section 4.4*. The other transition issues constituted all challenges and barriers in the system development as discussed with the system actors during the conducted interviews. In the ability to deal with the issues, again a dominant role is projected for industry and the network operator. Also, the governmental pro-activity is discussed, which insinuates that the market by itself is not fully able to deal with the expected barriers in the value chain development. The dominant role of the network operator and industry requires specific attention by public actors with a facilitating role.

8.1.6 Transition pathways

With all the information gathered in *chapters 4*, *5* and *7*, three routes are explored towards the visions of 2050 constructed in *chapter 6*. For the short-term, middle-term and long-term, actions, strategies and elements are divided over the three levels of analysis: actor network, visions and value chain. The routes can be summarized as follows. The diverging approach of the routes towards the three possible end-visions covers a wide variety in possibly faced transition challenges and mechanisms to deal with. This enabled the research to cover the wide spectrum of the influence the pipeline network has on, and how it is affected by, the development of the hydrogen value chain. Besides the construction of general key actions required in any situation, the pathways enabled the identification of five key aspects that should emphasize increased focus in the development of the hydrogen value chain by system designers:

- The type of pipeline is situation dependent and does not influence the development of the value chain. However, it is strongly affected by the role of hydrogen in the system, the transition strategy and demand sector targeted.
- Network ownership and operation. In the first phase of the transition period, many industrial pipelines are preferred to be operated privately. If the necessity for a connection to the public infrastructure fails to happen due to sufficient industrial demand to absorb all production volumes, this could cause deceleration of market development and upscaling of the network.

- Network strategy in transition phase. A consistent strategy, both institutionally and by system actors, provides the solid ground for optimal exploitation of efficient investments and energetic flows combined with upscaling of volumes. The strategy enables the system designer to deal with the complexity of the two roles that hydrogen can fulfil in its own value chain. Seven iterative steps are proposed to determine this strategy.
- Role network operator and industry. These actors are experiencing much power particularly in the transition phase. If this is not utilized in an effective manner, this could obstruct the development of the value chain. If there is a threat of failing by the market to organize this, a pro-active role of the government is desired.
- Pipeline capacity and outreach. The consensus this research provides is that the pipeline capacities determine the possibility and extent of volume flow. By focussing on pipeline capacities, the restricted view of sectoral scenarios can be interrupted and investment losses in abundant volumes can be prevented. Also, this aspect supports the effective utilization of the power of industry and network operator.

The exact substance in the pathways gives detailed interpretation to these aspects. The pathways explore strategic choices expected to be faced in the route towards three significantly varying end-situations. These aspects are the relevant concretised interpretations the general systems issues determined in *chapter 6*. They provide new insights with respect to common-known issues presented in *section 2.3.3*.

8.2 Discussion methods and context

8.2.1 Shortcomings methods

Modelling end-visions

The modelling of the end-visions by ETM is accompanied by simplifications since the ETM models the full energy system and simplifies some detailed elements of the hydrogen system. The model does not enable to model the transit flow of import and export, but only provides an import or export net volume on a yearly base. This inability presents a major shortcoming in the analysis being performed from the perspective of the Industrial Cluster of Rotterdam. The ICR is expected to fulfil a main role for transit flows with the port as hydrogen hub for Europe. The potential to assess this role is reduced by the inability to model this flow. The flow would probably have had a large impact on the outlook of the pipeline network since the standards are determined based on the main flow of hydrogen. If the main flow, is imported hydrogen, as in the third vision, it could have resulted in larger flows of ammonia, LH_2 or LOHC in the system.

Therefore, volumes based on demand of the area do not provide useful insight for the required network. Besides that, scaling of national visions to regional industrial visions in the ETM comes with many uncertainties and industrial feedstock demand could not be modelled on a regional scale. Therefore, it was decided to only provide the national end-visions. Although it provides relevant variety in context of the three end-visions, the quantitative modelling is limited.

Furthermore, it would have been interesting to gain more insights by the model in the flow of the different hydrogen purities in the system. The Sankey diagram provides only depictures the full flow. Also, the alignment and flow between hydrogen and renewable energy could not be fully determined but was tried to control by the capacities.

The focus on the hydrogen network as part of the total energy system, could have caused indirect irregularities to other, not observed, energy system components. The major aspects such as hours of blackout, loss of load, CO_2 reductions, costs of total energy system, share of renewables in energy mix and share of import were continuously monitored. However, more minor aspects on the background could have been affected by choices made in the hydrogen system.

Interviews as method

The semi-structured interviews provide the data on actor perceptions required for the analysis parts. However, the quality of the data is strongly determined by the in-depth knowledge of the problem domain by both researcher and interviewee. This skill was developed in the conceptual phase of the research by the systems analysis, but it is still difficult to comment on the content during the interviews, especially if interviewees attempt to provide more detail about their field of expertise. Ex post, the statements can be checked, but the ability to face up statements during the interviews can bring the quality of the derived data to higher levels. Therefore, It is not an easy method to obtain detailed information and time-consuming.

Actor analysis

In the pre-phase, it is essential to determine what actor analysis techniques are to be included, which depends on the context of the research. The basic actor analysis, power interest grid and actor-influence analysis are stepping stones and should be included independent of the context (Bryson, 2004). Beyond that, chosen techniques depend on the research objective. Not choosing the optimal techniques can strongly limit results of analysis later on in the process. Due to time constraints, choices had to be made on a trade-off between benefits and costs (in time) of the analyses and the full spectrum could not be covered.

Also, the inexistence of the public hydrogen system and the mixture of actor roles in transition period and end-situation increased the complexity in mapping and structuring of stakeholders. For some systems tasks it is not even clear what group of actors will be responsible, i.e. for instance for operation of the pipeline network.

Interviewing the market actors, it highly important to observe objectivity in their perceptions. The actors have interests and benefits, and this may increase subjectivity of their arguments. Although, in mapping of the actor perspectives, subjectivity plays a key role. This process gains in complexity since public state-owned enterprises also have an interest due to the desire to reuse the assets of the existing natural gas grid to avoid loss of investment and guarantee their existence in the future system.

The actors are assigned future roles based on current dynamics, but the fundament of a transition is that dynamics continuously change. Therefore, this approach increases the uncertainty of the results.

8.2.2 Validation of results

The validation of qualitative results on issues and transition pathways would require extra participatory interview rounds or, preferably, workshops to check whether the systems perspective, obtained from all actor perspectives, in the transition pathways complies with the general perception of the actors. By these rounds, the two other effects described by the framework of Hughes, i.e. from visions and value chain level of the actor network, can be analysed. Also, the dynamics within the actor network, such as mutual impact of actor decisions, could have been explored in workshops.

The quantitative counterpart of the end-visions is only validated during the research by the actors during the interviews but are thereafter adjusted on their comments. This should be validated again. Also, the viability can be more explored by simulation tools or extensive techno-economic modelling. The research covered the strategic aspect, but this should be complemented by modelling.

8.2.3 Generalizability of results

Generalizability of results to other regions with the same degree of certainty that quantitative analyses can, is not easy to accomplish with qualitative studies (Ochieng, 2009). The results can be significant due to chance and external circumstances to accounted for or not observed.

However, the framework combining the different levels of analysis can be applied in any situation where the role of an element in the development of the hydrogen value chain is to be quantitatively assessed. The framework is composed in such general form that it should not necessarily be deployed for the pipeline network. It can also be applied to explore the role of electrolysers, tube trailers, conversion techniques etc. The results are presented in most general form, so they are not bounded by regional constraints.

The results show the transition pathways from the development the hydrogen value chain, and the role of the pipeline network in this process, from the perspective of the industrial cluster of Rotterdam. For other industrial clusters in the Netherlands the results of this research can provide guidance in determining their perspective. Two important notes should be made. The level of importance of internationalisation, import and export, is higher for the ICR than for other clusters. Also, the focus on transition technologies may be location dependent. Rotterdam has a strong focus on development of blue hydrogen to high heating demand and the strategic location near the North Sea to perform CCS. The industrial cluster in Groningen, for instance, do not have these advantages and may not consider blue hydrogen to the extent the ICR does. So, although, general issues and aspects determined in this research may hold for all clusters. Some aspects are context specific. The framework can be applied in any case and the results of this research can be used to set a concise focus in the early phase of the research.

8.2.4 Societal and scientific relevance

This research contributes to the societal need for the decarbonization of the energy system and the reduction of carbon emissions. The intended transition from natural gas to hydrogen has impact on society and people's lives in the built environment. However, among all alternatives for natural gas, hydrogen exhibits the low negative impacts on daily activities.

Scientifically, this research contributes to the development of hydrogen transportation by pipeline, taking into account the actor complexity and the development of the future value chain. The outcomes of the project are scalable, transferrable and oriented towards further development of the infrastructure in a national and international context. Attacking the problem from a strategic systems perspective focusing on qualitative arguments and on the development of the value chain instead of the supply chain offers new perspectives to the discussion on the emergence of hydrogen transport in the future hydrogen system.

The assessment of all actor perspectives covering the wide variety in interpretation and perception of value chain elements showed that, one specific element can be viewed as many things. Let alone, the role of hydrogen in general. This research showed that there is no consensus yet on many critical issues in the development of the hydrogen system. The consensus among system actors is essential for effective cooperation and an efficient transition period.

8.3 Conclusion

This research explored the challenges and barriers being faced in the development of the hydrogen value chain, with the pipeline network as main element of focus. By applying a systems perspective that is oriented from the role of the network infrastructure, it was aimed to deal with the complexity of the interdependent development of production, infrastructure and demand. The research is unique in combining three hydrogen cycles, of green, blue and 'yellow' hydrogen, with different demand sectors with varying product requirements in one approach. The two product flows present in the cycles, hydrogen as energetic source for heat and hydrogen as chemical product, have as consequence the complexity of dealing with two transitions at once; the transition from a natural gas network to a hydrogen network and the transition that develops the hydrogen network as chemical product value chain. The combination of the hydrogen cycles with the investigation of the two transitions at once, increases the complexity to a large extent, but also safeguards the unique character of this research.

All the applied analyses throughout the research resulted in the construction of three transition pathways; 'H_2 - High Purity', 'H_2 - Low Purity' and 'H_2 - Mixed Purity'. The outline of these pathways has already been described in the conclusion in *section 7.6*. The transition pathways aimed to explore the consequences, of the systems complexity described in the paragraph above, for the development and operation of the pipeline network. It can be generally concluded that the type of pipeline majorly depends on the availability of existing natural gas pipelines. This availability depends among other things on if the location of the existing pipelines matches the location of the required supply and demand flow, on the spatial complexity of the required network in a particular sector and on the general function of hydrogen in the system that affects the remaining demand for natural gas. If the determined factors show negative consequences for availability of existing pipelines, new dedicated pipelines are constructed. Physical blending is not considered as feasible alternative by the system actors.

Next to the type of pipeline, the key aspects of the pipeline network are summarized in four other aspects, so five in total: network ownerships and operation, network strategy in transition phase, the role of network operator and industry, and the pipeline capacity and outreach. The interpretation of these five aspects by the actor regime during the transition period influence the long-term development of the hydrogen value chain. This causality defined the lock-in effects, defined by:

- The extent of market expansion;
- The security of supply; by connection to seasonal storage and liquidity of national backbone;
- Sufficient pace of upscaling of volumes;
- Energetic and economic efficiency of the system;
- International connectivity;
- Level of fair competition; due to possible centralisation of power and resources around the industrial cluster;

The lock-in effects provide the lessons learned that should be considered by other industrial clusters in the Netherlands investigating the development of the hydrogen value chain. By facing the full value chain complexity, this research obtained new insights into the influence of short-term actions related to actor dynamics and the pipeline network on the long-term transition to the hydrogen value chain.

8.4 Recommendations future research

Following the discussion in the previous section, some recommendations can be provided for future research. Validation of the qualitative results could be obtained by participative workshops, while extensive techno-economic modelling and simulation models can validate the pathway flows and end-visions. Furthermore, the impact on volumes of a continuous import and export flow of hydrogen could be modelled to complement the perspective of the ICR by the international character. The strategic decisions can be assessed further into detailed actions. This could provide more focus on the, not assessed, dynamics of the research framework; the effects on the actor network.

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Appendix A

Scientific paper

Is included as a completely separate document.

Appendix B

Literature study

Search Method

The search for articles to be used in a literature review can be outperformed in different ways, dependent on the type of articles needed and field of research. In this light, two techniques are considered to be relevant. A researcher can choose to start with search strings in different databases or start with a set of papers of which reference lists are screened for further relevant articles, often referred to as respectively database search and backward snowballing (Jalali & Wohlin, n.d.). In this research, the first selection of articles is provided by database search by use of the keywords Transition hydrogen economy, infrastructure and pipeline. These keywords used in the web of science database provided the set of papers that thereafter formed the base for the backward snowballing process. This technique was chosen since it offers the possibility to adjust the selection of relevant aspects of the literature study as the search continues and offers a broader view towards the formulation of the research question. The development of the hydrogen economy and its infrastructure is a frequently investigated topic over its wide variety of applications and backward snowballing enables the researcher to present a fully comprehensive overview of the currently performed research to the reader. The overview of this literature research is presented in the main text, while the table with general information and findings on all literature is presented in here.

Selection of aspects

The studies are all reviewed based on several aspects to determine the characteristics and dimensions of the research on the assigned problem areas so far. By asking the questions below, a deliberate structured overview could be made of the knowledge area.

- What type of study is performed?
- What is the geographical area of focus?
- What are the elements and dimensions studied?
- What are the main findings?
- What are described shortcomings of the research and recommendations for further research mentioned?

Author	**Year**	**Title**	**Area**	**Type of study**	**Elements studied**	**Main findings**	**Challenges described**
Hennicke & Fischedick	2006	Towards sustainable energy systems: The related role of hydrogen	Global, Germany	Scenario study	Efficiency increase; Structural change of system	No sense to speed up hydrogen before 2030. Contribution of hydrogen up to 2030/2040 will be low. After 2030/40, forced market introduction of hydrogen. Flexible system could be developed by forcing efficiency improvements and integration of social and technical innovations.	Combined strategies for efficiency increase and decoupling wealth from resource flows. New patterns of social and technological revolution.
Hisschemöller, Bode & van de Kerkhof	2006	What governs the transition to a sustainable hydrogen economy? Articulating the relationship between technologies and political institutions	Netherlands	Theoretical institutional analysis	4 paradigms of governance: Governance by policy networking, governance, corporate business and challenge	No neutral or optimal frameworks for policy making exist where competing hydrogen options are at stake. Low-profile governance might fail to make the transition to hydrogen-based economy, because collective good character of heavy infrastructure or because advance options are being excluded.	Dutch stakeholders assumed the question whether introduction of hydrogen by blending or making an immediate shift to a full hydrogen infrastructure the most critical. Relationship between technologies and institutions is focus of ongoing research.
Edwards, Kuznetsov and David	2007	Hydrogen energy	Literature study	Scientific, technological and socio-economical barriers	4 major hurdles to achieve vision of hydrogen economy: Develop and introduce cost-effective, durable, safe and environmentally desirable hydrogen systems. To develop infrastructure to provide hydrogen. Reduce sharply production costs from RES over decades. CCS from reforming processes.	Scientific breakthroughs Technological development coupled with continued social and political commitment	
Marbán & Valdés-Solís	2007	Towards the hydrogen economy?	Global	Theoretical study	Link of hydrogen supply chain to the transition towards the hydrogen economy	Two conditions must be met for society based on hydrogen economy: International organizations must be strong enough to guarantee fulfilment of agreements on CO2 reduction. Technological development must bring cost reduction of hydrogen technologies.	-
Bleischwitz & Bader	2010	Policies for the transition towards a hydrogen economy: the EU case	EU	Policy analysis	EU energy policies, EU regulatory policies, EU spending policies	EU policy framework does not hinder hydrogen development, but does not push it either. Large-scale market development of hydrogen will require new policy approach which comprises technology-specific support and supportive policy framework with regional dimension.	Future policy framework should meet following requirements: Strong EU energy policy with credible long-term targets, better coordination of EU policies, regions with strong hydrogen clusters can advance market introduction and establish first hydrogen infrastructure

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Andrews & Shabani	2012	Re-envisioning the role of hydrogen in a sustainable energy economy	Global	Strategic analysis	Six principles that guide role of hydrogen in energy strategies	(1) Hierarchy of value chain heavily relies on local RE sources. (2) Complementary use of hydrogen and electricity to minimize new hydrogen pipeline networks. (3) Production of hydrogen from RE. (4) Complementary hydrogen and battery storage. (5) Seasonal hydrogen storage to balance centralized grids relies on RE input. (6) Bulk hydrogen storage as strategic energy reserve relies heavily on RE.	Hydrogen storage highly integrates with electricity system. The technical feasibility of large-scale storage of hydrogen. Development of liquid hydrogen appliances.
Ball & Weeda	2015	The Hydrogen economy - Vision or reality?	-	Systems Analysis	-	Hydrogen as policy priority first as fuel in transport sector. Recent years, hydrogen electrolysis as flexibility option for intermittent renewables gains attention. Hydrogen with electricity could provide backbone of a future.	Public-private partnerships aim to develop market for hydrogen appliances, such as mobility, how will this work out? Hydrogen should be evaluation in conjunction with various alternatives, not in isolation.
Moliner, Lázaro, Suelves	2016	Analysis of the strategies for bridging the gap towards the hydrogen economy	Global	Strategic analysis	Strategies on production, distribution and use	Short-term focus on fuel cell vehicles. Rising NG prices and credits from avoided CO2 emissions will cause hydrogen from RE surplus to be competitive in medium term (2030-2040). Then hydrogen could be in NG grid (pure or blended). In long-term, RE hydrogen independent from electricity grid will be implemented.	Further research of strategies encompassing production, distribution and utilization of hydrogen on solid grounds of science and engineering. Role of hydrogen in future scenarios should not be considered in dominance, but in competition and complementarity with other energy carriers.

Table 11: *Literature study: part hydrogen transition.*

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Mueller-Langer, Tzimas, Kaltschmitt, Peteves	2007	Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term	Europe	Techno-economic analysis	Production: SMR, coal and biomass gassifciaton, electrolysis.	Industrial large-scale processes, using natural gas and coal, will constitute the most important routes. Biomass important if technological barriers are overcome. Electrolysis only practical for niche applications due to high electricity costs especially from RES.	Elaborated optimization on economic balance between hydrogen production, storage and distribution infrastructure dependent on region-specific needs.

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Quarton & Samsatli	2020	The value of hydrogen and carbon capture, storage and utilisation in decarbonising energy: Insights from integrated value chain optimisation	UK	Value chain optimisation	Integration of hydrogen and CCS technologies in existing energy sectors	On the long-term, RE + hydrogen storage offer flexibility and decarbonisation at lower cost than fossil + CCS. For CCS to become attractive, decarbonisation of industry and negative emissions policies are required. CO2 price of £130/t required for CCS to become part of system, or policies required.	Interest in negative emissions technologies. Research into whether power-to-gas can be scale up sufficiently quickly, otherwise more focus on production from fossil with CCS.
Partidário, Aguiar, Martins, Rangel, Cabrita	2019	The hydrogen roadmap in the Portugese energy system - Developing the P2G case	Portugal	Value chain assessment	Technologies of P2G value chain in combination with injection in gas grid (blending)	Technology maturity along value chain is crucial. If technical performance criteria are not met, electrolysis is not applicable. P2G strategy is promising but involves challenges regarding injection as transportation. H2 approach is case sensitive.	Careful decisional processes are required for implementation of hydrogen approaches. Continuous value chain assessment requirement since it differs along main lifecycle stages.
Samsatli & Samsatli	2019	The role of renewable hydrogen and interseasonal storage in decarbonising heat - Comprehensive optimisation of future renewable energy value chains	UK	Optimization model	Design, planning & operation of renewable hydrogen value chain with injection in gas grid	Optimal pathway to heat is roughly 20% hydrogen and 80% electricity. Hydrogen storage is key enabling technology. Hydrogen is assumed to be low-carbon alternative energy carrier for natural gas because of its suitability for large-scale, long- and short-term storage and low transporation losses, which helps to overcome intermittency and seasonal variations in renewables.	Determine impact of different levels of hydrogen injection into the gas grid; considering other potential energy carriers such as syngas, methanol, ammonia and examining the role they may have in low-carbon future. Investigating importance of a strong hydrogen supply chain in enabling CCUS. Robust optimistaiton to ensure that solutions are resilient to uncertainties.
Almansoori & Shah	2009	Design and operation of a future hydrogen supply chain: Multi-period model	UK	Optimization model	Systems perspective simulated an optimal supply chain. Variation of hydrogen demand impact on infrastructure development.	First, small size-plant together with using hydrogen currently produced by chemical processing plants. Transport by liquid hydrogen trucks and various storage facilities. Centralised production for industry	-
Nunes, Oliveira, Hamacher, Almansoori	2015	Design of a hydrogen supply chain with uncertainty	UK	Optimization model	Uncertainty in hydrogen production, storage and usage	Methodology for design of a hydrogen supply chain while considering the inherent uncertainty associated with the demand for this fuel in the future.	Further optimization.
Reuß, Grube, Robinius, Preuster, Wasserscheid, Stolten	2017	Seasonal storage and alternative carriers: A flexible hydrogen supply chain model	N.a.	Techno-economic analysis	Role of storage and alternative hydrogen carriers	Shows relevant infrastructure technologies and combinations from ecological and economic aspects. LOHC is very promising for future hydrogen supply chains from an economic point of view. Seasonal storage may have high economic impact, especially liquefaction of hydrogen.	-

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Breyer, Tsupari, Tikka, Vainikka	2015	Power-to-Gas as an emerging profitable business through creating an integrated value chain	N.a.	Business analysis	Integration of PtG systems in the value chain	PtG needs to utilize value of all products and services to establish sustainable business models. Breakthrough of PtG would create new market segments such as seasonal storage or balancing of RE production. Not unlikely that PtG is more relevant for supporting decarbonization of transportation sector and chemical industry	-
Farahani et al.	2019	A hydrogen-based integrated energy and transport system	N.a.	Simulation study	Technical feasibility, controllability of supply and demand.	FCEV's can serve as a power plant, next to storage unit.	Grid modeling for future research, so hydrogen grid next to electricity grid to investigate combination of battery and FCEV's and consequences for system and costs.

Table 12: *Literature study: part hydrogen value chain.*

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Jo et al.	2006	Analysis of hazard area associated with hydrogen gas transmission pipelines	-	Mathematical analysis	Safety, hazard area	Hazard area is important in safety management of high-pressure pipelines transporting hydrogen gas and the hazard distance found is 300 m.	-
Witkowski et al.	2017	Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects	-	Mathematical analysis	Safety, pipeline characteristics, compression, transportation	Challenge is to develop a reliable, cost-effective and energy efficient compression technology for the minimum mass flow rate. Hazard distance depends on hydrogen pressure and size of damage.	-
Scott & Powells	2020	Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment	UK	Social analysis	Safety, social impact, hydrogen injection	People are reluctant towards cooking/heating with H2 due to flammability and explosivity. People feel that being forced to pay more for H2 is both unavoidable and detrimental to already existing fuel poverty. Development of hydrogen for homes is being led by gas network operators in collaboration with governmental and industrial actors.	Shape emerging hydrogen agenda to critically foreground the social, economic and justice implications.
Lins & Almeida	2012	Multidimensional risk analysis of hydrogen pipelines	-	Mathematical analysis	Human, environmental and financial risks	The paper provides a parameter to help the decision-maker in deciding where to apply investments in maintenance, operating, monitoring, safety and so forth.	Do the research for natural gas pipelines as well to be able to make comparison between the two.

Table 13: *Literature study: part safety.*

Author	**Year**	**Title**	**Area**	**Type of study**	**Elements studied**	**Main findings**	**Challenges described**
Partidário, Aguiar, Martins, Rangel, Cabrita	2019	The hydrogen roadmap in the Portugese energy system - Developing the P2G case	Portugal	Value chain assessment	Technologies of P2G value chain in combination with injection in gas grid (blending)	Electrolysis with injection in gas grid enables: decarbonization of transition fuel, promotion of RE integration and storage solutions, management of RE surplus and promotion of sector coupling.	-
Quarton & Samsatli	2020	Should we inject hydrogen into gas grids? Practicalities and whole-system value chain optimisation	UK	Value chain optimization	Opportunities and challenges for hydrogen injection	Injection of hydrogen into existing natural gas grids could decarbonise heat and take advantage of inherent flexibility that gas grids provide in low-carbon future. Partial hydrogen injection could provide steppingstone for developing hydrogen infrastructure, but large-scale decarbonisation requires complete conversion to hydrogen.	Properties of gases. Need for low-cost, low-carbon hydrogen supply chain. Whether full conversion of gas grid to hydrogen is preferable to electrification depends on value of gas grid linepack flexibility and the cost of expanding electricity infrastructure.
De Vries et al.	2017	The impact of natural gas/hydrogen mixtures on the performance of end-use equipment: Interchangeability analysis for domestic appliances	-	Mathematical analysis	Technical feasibility of blending and impact on end-use appliances in built environment	The maximum hydrogen addition depends on the composition of the natural gas, this adds another dimension of complexity to the grid-management of hydrogen addition. Roughly up to 10% H2 in these mixture causes no increase in risk for the appliance population, for fuel lean appliances this value is higher.	Strategic roadmaps and assessment and testing programs for introduction of hydrogen in natural gas infrastructure without increasing the risk for the domestic end user. Contribution to the ultimate role of PtG. The analysis should be performed for regional/national natural gas compositions instead of fictitious distribution range.
Pellegrino et al.	2017	Greening the gas network – The need for modelling the distributed injection of alternative fuels	-	Mathematical simulation	The upper constraint of hydrogen injection into natural gas grid; Wobbe-index.	10 % hydrogen is upper constraint. Injection of hydrogen shows the possibility of energy integration between electrical and gas networks. Variations in pressure drops, Wobbe-index, higher heating values and gas gravity as consequence of blending.	Determining impact of renewable technology on infrastructure where it is expected to operate.
Hafsi et al.	2017	Numerical Approach for Steady State Analysis of Hydrogen–Natural Gas Mixtures Flows in Looped Network	-	Mathematical analysis	Behaviour of hydrogen-natural gas mixture in pipeline networks	Hydrogen rises pressure drop values and increases gas velocity in network. Compressor stations need to compensate for this pressure drop. Uncertainty regarding other chemical components in mixture than hydrogen and methane.	-
Kuczyński et al.	2019	Thermodynamic and Technical Issues of Hydrogen and Methane-Hydrogen Mixtures Pipeline Transmission	-	Mathematical analysis	Behavioural limits of hydrogen and hydrogen-natural gas mixtures in pipelines	Maximum participation of hydrogen in natural gas should not exceed 15-20%, otherwise the gas loses its required standard. Pipeline transmission of the mixture requires larger pipeline diameter for same volume flow rate. Since outlet pressure is lower for mixture, the maximum transportation distance is higher than for pure natural gas.	-

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Timmerberg & Kaltschmitt	2019	Hydrogen from renewables: Supply from North Africa to Central Europe as blend in existing pipelines – Potentials and costs	North Africa/Europe	Techno-economic analysis	Technical and economic feasibility of transporting renewables from Africa to Europe by converting to hydrogen and blending in natural gas pipelines	Necessary compressor power for H2 is 3.3 times higher than for natural gas. If natural gas system is adjusted, shares of H2 up to 50% seem to be possible. Low GHG methane from power-to-gas process could substitute natural gas. Transportation of H2 in existing natural gas pipelines is most economical option; better than transforming first to methane.	-
Witkowski et al.	2018	Analysis of compression and transport of the methane/hydrogen mixture in existing natural gas pipelines	-	Risk analysis	Compression and pipeline transport of natural gas/hydrogen mixture with safety issues	Purification and separation is used to extract hydrogen from natural gas close to point of end-use. Until 15% presents minor issues. 15-50% addresses more significant issues. Above 50% presents challenging problems regarding pipeline materials, safety, modifications for end-use appliances.	-
Gondal	2018	Hydrogen integration in power-to-gas networks	Europe	Technical analysis	Effect of hydrogen injection on the existing natural gas pipeline infrastructure	50% hydrogen is not critical in transmission lines, but allowable concentration in gas turbines and compressors is 20% and 10% resp. End-use appliances are at least able to receive 20% hydrogen concentration. Calorific value is affected in 10% mixture.	Simulation studies on all physical and chemical features of the H2/NG networks

Table 14: *Literature study: part blending.*

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Smit et al.	2006	Hydrogen infrastructure development in The Netherlands	Netherlands	Techno-economic analysis	Demand development, infrastructure costs, type of transportation ,type of production	Hydrogen demand estimated at 2200 kton/yr. Through small-scale on-site production, the hydrogen demand will develop to such an extent that construction of pipeline infrastructure will become viable around 2030. Costs for fully developed infrastructure are 12000-20000 million €.	Development may start in other regions than Rotterdam or in industrial regions abroad. Natural gas/hydrogen mixture can boost widespread use of hydrogen. NTP from start can incentivize demand for pure hydrogen applications and implementation of renewables.

Author	**Year**	**Title**	**Area**	**Type of study**	**Elements studied**	**Main findings**	**Challenges described**
Baufumé et al	2013	GIS-based scenario calculations for a nationwide German hydrogen pipeline infrastructure	Germany	Spatial modelling, demand development, fueling infrastructure, type of production, infrastructure costs	Existing gas network is proposed as preferred route for future hydrogen network.High share of fixed costs for small diameter pipelines, so other delivery options can be expected for low demand stations. Transmission network is €5 - €8.5 billion and 8900 - 12600 km. Distribution network is €8.2 - €13.7 billion and 13000 - 28000 km.	Calculation assumptions based on current situation. Consider time variability in supply and demand.	
Tzimas et al.	2007	The evolution of size and cost of a hydrogen delivery infrastructure in Europe in the medium and long term	Europe	Techno-economic analysis	Demand development, infrastructure costs, type of transportation	On short-term, infrastructure will rely on medium pressure centralised structure parallel to natural gas. On medium term natural gas system will be converted. Long-term, high pressure transmission lines are unnecessary because hydrogen will be associated with distributed power system based on renewables. 1-4 million km distribution pipelines. 35 000 km high-pressure and 400 000 km medium pressure transmission pipelines. 3000-8000 trucks. Costs are 700-2200 billion euros.	-
Tlili et al.	2020	Geospatial modelling of the hydrogen infrastructure in France in order to identify the most suited supply chains	France	Supply chain optimization, facility location, demand development ,hydrogen storage	Increase in market penetration causes large drop in hydrogen price at the pump. Hydrogen production near demand is essential in first market penetration phase. For higher penetration rate, electrolysers next to electricity source is more viable.	-	

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Agnolucci et al.	2013	The importance of economies of scale, transport costs and demand patterns in optimising hydrogen fuelling infrastructure: An exploration with SHIPMod (Spatial hydrogen infrastructure planning model)	-	Supply chain optimization	Demand development, type of production ,infrastructure costs, hydrogen costs, CCS	Tendency is shown for large centralised production facilities. Lower transportation costs for liquified hydrogen compensate costs of liquification. Demand assumption tend to be downplayed in literature, but are extremely important.	Pipeline transportation of hydrogen should be introduced. Link SHIPMod to energy system model to assess effect of different level of hydrogen demands, resulting from optimised energy system, on the infrastructure required to meet demand.
Johnson & Ogden	2012	A spatially-explicit optimization model for long-term hydrogen pipeline planning	USA	Spatial modelling	Demand development, production facilities pipeline specifications, infrastructure costs	Pipeline costs are divided over demand centers (cities) according to utilization of pipeline. Location and size of production facilities.Location and size of pipelines.	Include multiple centralized production types. Examining different assumptions about pipeline and production expansion.
Balta-Ozkan & Baldwin	2013	Spatial development of hydrogen economy in a low-carbon UK energy system	UK	Spatial modelling	Demand development, type of production, type of transportation, pipeline specifications, emissions	Hydrogen delivery costs and dimensions of pipelines. Only after 2040, the increased demand justifies the expansion of network. Variable hydrogen demands in transport sector influenced by fuel prices. Centralised or decentralised depends on wider energy system and supply and demand regions.	Population as key driver of hydrogen network development should be studied further.
André et al.	2013	Design and dimensioning of hydrogen transmission pipeline networks	France	Techno-economic analysis	Infrastructure costs, pipeline specifications, facility location	Two stage-approach of minimizing network length and then optimizing pipe diameter for fixed topology is not sufficient. Increasing total length of network can decrease costs by using smaller diameters for some pipes.	Optimal facility location/allocation problem for multi-source network.
Reuß et al.	2019	A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany	Germany	Supply chain optimization	Infrastructure costs, demand development, type of transportation, emissions, fuelling infrastructure	Optimal scenario is salt cavern storage, pipeline transmission and truck distribution. Distribution by pipeline only relevant for high hydrogen demand densities. Demand-oriented electrolysis or expansion of analysis to different countries would lower distance between production and demand.	Electricity costs of the electrolysis and fuelling station investment costs are main issue to solve. Storage and transport costs are only 16% of total supply chain costs.
Moreno-Benito et al.	2017	Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development	UK	Supply chain optimization	Infrastructure costs, demand development, type of production, type of transportation, CCS, emissions, import	Hydrogen production from natural gas by SMR with CCS is most cost-effective with low emissions. High correlation between pipeline infrastructure and type of hydrogen production. Levels of import and national production are consistent for all cases. Eliminating CCS, gives preference to import and distributed electrolysis.	Introduction of storage dynamics for modelling hydrogen consumption and supply mismatches. Proposed framework can also be applied to analysis of other future hydrogen economies.

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Han et al.	2013	Multi-objective optimization design of hydrogen infrastructures simultaneously considering economic cost, safety and CO2 emission	Korea	Mathematical analysis	Cost efficiency H_2 supply, safety, emissions	Hydrogen will replace carbon-based fuels. Electrolysis is most efficient with pipeline transportation, where SMR is more efficient with transport by tanker trucks. Decentralised production corresponds to electrolysis, but with higher shares in RE, centralised production could be beneficial.	-
André et al.	2014	Time development of new hydrogen transmission pipeline networks for France	France	Spatial modelling	Infrastructure costs, pipeline specifications	Short/mid-term perspective (before 2025), trucks are most economical. Long-term (beyond 2025), pipelines are viable as soon as hydrogen share in car fuelling market reaches >10%.	Consider several sources of hydrogen, also underground storage facilities. Facility location problem. Other topologies than tree-like network.

Table 15: *Literature study: part dedicated infrastructure.*

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Haeseldonckx & D'haeseleer	2007	The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure	-	Techno-economic analysis	Hydrogen injection, transition issues, market structure	Decision to start using H2 instead of natural gas can only be made on a European level since European countries are transit countries for natural gas. Need to use piston compressors for higher required pressure of H2. Transition towards hydrogen economy by H2/NG mixture in existing NG network is possible in both regulated or liberalised market. Transport grid is stumbling block.	Transport grid is stumbling block. For full implementation of hydrogen network, this need to be overcome.
Dodds & Demoullin	2013	Conversion of the UK gas system to transport hydrogen	UK	Techno-economic analysis	Conversion costs, technical feasibility, safety, network capacity, policy	Hydrogen can be transported safely in low-pressure pipes. High-pressure pipes can not be used due to embrittlement. Concerns over reduced capacity (20% lower) of the system and much lower linepack storage (75% lower) compared to NG. Decision to convert the system largely depends, besides economic factors, on relative performance of technologies and willingness of government to organise conversion program.	-

Author	Year	Title	Area	Type of study	Elements studied	Main findings	Challenges described
Ma & Spataru	2015	The use of the natural gas pipeline network with different energy carriers	UK	Techno-economic analysis	Production costs, injection costs of gasses	National transmission system is not suitable for hydrogen, only regional distribution system. New system should be build if high pressure hydrogen pipeline is needed. Total injection costs of H2 from RE slightly increase with the injection rate and are higher than for natural gas. Wind generated hydrogen is recommended and the conversion of the existing natural gas system is recommended by injecting to 20%.	The transmission pipelines and compressors should also be considered.
Wang et al.	2018	An MILP model for the reformation of natural gas pipeline networks with hydrogen injection	-	Supply chain optimization	Pipelines specifications, facility locations, hydrogen injection, infrastructure costs	Substitutions, location of compressor stations and operating pressures can be obtained according to percentage of hydrogen injection. Design pressure of some segments should be increased. Considering expansion and reformation of existing network simultaneously gives more economic results.	-
Speirs et al.	2018	A greener gas grid: What are the options?	-	Techno-economic analysis	Type of gas, conversion costs, emissions	There is no clear best option regarding gas decarbonisation. The comparison between biomethane and H2 should not only be based on cost but on full suit on flexibility options. The estimates on cost and GHG emission for all decarbonised gas options vary over significant range.	Further research is needed to understand suitability of existing networks for decarbonised gas and level of decarbonisation achievable. Need for policy on hydrogen standards, transparent funding models and gas standards for lowest GHG emissions.
Hickey et al.	2019	Is there a future for the gas network in a low carbon energy system?	-	Scenario analysis	Demand development, future infrastructure	In 2015-2030 period gas use increases and will reach its highest level of consumption.2030-2050, shortfall in demand leads to potential disconnections from distribution network. Gas industry should align strategy for remaining competitive with low carbon policy objectives.	

Table 16: *Literature study: part reuse existing grid.*

Appendix C

Systems analysis

Institution	Title	Year of focus	Scope	System components	Reference
DNV GL	Energy Transition Outlook 2019	2050	Global	Offshore wind	(DNV GL, 2019)
IEA	The Future of Hydrogen	2030 + long-term	Global	Full chain	(IEA, 2019b)
IEA	Offshore wind outlook 2019	2040	Global	Offshore wind	(IEA, 2019a)
Hydrogen Council	Path to hydrogen competitiveness. A cost perspective.	2050	Global	Offshore wind, economics	(Hydrogen Council, 2020)
EKZ	Government Strategy on Hydrogen	n.a.	Netherlands	General strategy	(Ministry of Economic Affairs and Climate Policy, 2020a)
n.a.	The Future of Gas in Europe	2050	Europe	Natural Gas	(Catuti, Egenhofer, & Elkerbout, 2019)
H-vision	Blue hydrogen as accelerator and pioneer for energy transition in the industry	2030	Rotterdam	Blue H2 chain	(H-vision, 2019)
Gasunie & TenneT	Infrastructure Outlook 2050	2050	Netherlands	Full chain	(Gasunie & TenneT, 2019)
TKI Nieuw Gas	Outlines of a hydrogen roadmap	2050	Netherlands	Full chain	(TKI Nieuw Gas, 2018)

Institution	**Title**	**Year of focus**	**Scope**	**System components**	**Reference**
Wuppertal Institute	Decarbonization pathways for the industrial cluster of the Port of Rotterdam	2050	Rotterdam	Industrial chain	(Samadi et al., 2016)
CE Delft	Feasibility study into Blue Hydrogen	2030	Netherlands	Blue H2 chain	(CE Delft, 2018a)
EKZ	Rotterdam CCUS Project Porthos	2030	Rotterdam	CCS	(EZK, 2019)
CE Delft	Waterstofroutes Nederland	2050	Netherlands	Full chain	(CE Delft, 2018b)
Berenschot & TNO	CO2-vrije waterstofproductie uit gas	2050	Netherlands	Blue H2 chain	(Berenschot & TNO, 2017)
Berenschot & Kalavasta	Klimaatneutrale energiescenario's 2050	2050	Netherlands	Full chain	(Berenschot & Kalavasta, 2020)
DNV GL	Verkenning waterstofinfrastructuur	n.a.	Netherlands	Pipelines	(DNV GL, 2017)
GRT Gaz	Technical and economic conditions for injecting hydrogen into natural gas networks	2050	n.a.	Pipelines	(GRTgaz, 2019)
NREL	Blending hydrogen into natural gas pipeline networks: a review of key issues	n.a.	n.a.	Pipelines	(Melaina et al., 2013)
CE Delft	Net voor de Toekomst	2050	Netherlands	Full chain	(CE Delft, 2017)
Port of Rotterdam	Port vision 2030	2030	Rotterdam	Strategy	(Port of Rotterdam, 2019)
n.a.	Risks and opportunities associated with decarbonizing Rotterdam's Industrial Cluster 2050	Rotterdam	Strategy	(Schneider, Lechtenböhmer,	Samadi, 2019)

Institution	**Title**	**Year of focus**	**Scope**	**System components**	**Reference**
DNV GL	Taskforce Infrastructure Klimaatakkoord Industry	2050	Netherlands	Industrial chain	(DNV GL, 2020)
European Commission	The European Green Deal	2050	Europe	Strategy	(European Commission, 2019)
Hydrogen Council	Hydrogen scaling up: A sustainable pathway for the global energy transition	2050	Global	Strategy	(Hydrogen Council, 2017)
Navigant	The optimal role for gas in a net-zero emissions energy system	2050	Global	Full chain	(Navigant, 2019)
Netbeheer Nederland	Toekomstige gasdistributienetten	2050	Netherlands	Distribution	(Netbeheer Nederland, 2018)
Port of Rotterdam	Three steps towards a sustainable industry cluster Rotterdam-Moerdijk 2050	2050	Rotterdam Industrial chain	(Port of Rotterdam, 2018)	
TKI Nieuw Gas	Overzicht van Nederlandse waterstofinitiatieven, -plannen en -toepassingen	n.a.	Netherlands	Strategy	(TKI Gas, 2017)
ISPT	Hydrohub HyChain 1 + 2	n.a.	Netherlands	Full chain	(ISPT, 2019a, 2019b)

Table 17: *Overview of scenario and strategy reports studied and used in the research.*

Additional elements systems analysis

Natural gas

Currently, the estimates on the share of natural gas as a resource in the production of hydrogen in the Netherlands is between 73% and 80%. This accounts for 10% of the natural gas production (Ministry of Economic Affairs and Climate Policy, 2020a). The remaining production comes from hydrogen as a by-product in industrial processes. The majority of the companies use SMR, but ATR is also favored by some producers in both the Netherlands and Rotterdam

(Berenschot and TNO, 2017; CE Delft, 2018b). Both production technologies require natural gas as resource, with significant CO2 emissions. Natural gas is used both as fuel and as feedstock in the reforming processes. Roughly 30-40% is incinerated to fuel the process, resulting in a diffuse CO2 flow, while the other 60-70% is split using SMR or ATR into hydrogen and a concentrated CO2 flow (IEA, 2019b). The supply of natural gas will be increasingly dependent on import in the future because of the closing of the Groningen gas field in 2022, although the 450 small gas fields in the Eastern part of the country are kept economic for the coming years (Gasunie and TenneT, 2019). Therefore, the reforming installations are designed to run on high-caloric gas, which is the imported gas and the gas from the small fields, and not on low-caloric gas, which is the Groningen gas (H-vision, 2019). Because of this political decision and the market penetration of decarbonized alternatives for natural gas, its future role becomes uncertain. Scenarios with GHG emissions reductions targeted at 80% still describe as role for natural gas as an energy carrier. Regarding the hydrogen value chain, the role of natural gas is inherently determined by the utilization of CCS (Catuti, Egenhofer, & Elkerbout, 2019). It is hard to determine the future volume flow of natural gas in the Netherlands, since this fully depends on the deployment of SMR and the role of blue hydrogen in the energy transition. Furthermore, the natural gas price is highly unpredictable. Currently, the fuel costs for hydrogen made from natural gas account for 45-75% of the total production costs (IEA, 2019b). Other reports present estimates between of 70-80% of the total production costs (TKI Nieuw Gas, 2018).

CCS

The reforming processes emit roughly 9 kg CO2/kg H2, if no CCS is used (TKI Nieuw Gas, 2018). Without CCS, the Netherlands are likely to fail in meeting the targets of the Paris climate agreement. However, the capture rate of both installations is not perceived as a technical challenge, but is likely to be encountered from an economical perspective. Above these ranges, the costs to capture the last molecules of CO2 increase dramatically (CE Delft, 2018a; Navigant, 2019). Therefore, the definition of the term ‘blue hydrogen’ can be argued. While many studies and reports refer to blue hydrogen as an energy carrier with zero emissions, it still emits a small amount of CO2, dependent on technology used and on scale of the production site. The CO2 should be captured and stored in depleted gas fields under the seabed of the North Sea or utilized in industrial and other sectors, such as horticulture and the soda industry. At this moment, the government approved the storage under the North Sea and the first CO2 should be stored in one of the Porthos fields in 2022-2023 as presented in the figure below (of Economic Affairs & Policy, 2019). The storage capacity under the North Sea is 1400 Mton, while onshore storage capacity is 900 Mton. Nevertheless, onshore underground storage is still prohibited. When 10 to 50 Mton CO2 is stored annually, the storage potential should provide capacity for the coming 30 years (TKI Nieuw Gas, 2018).

The economic viability of CCS is largely determined by the CO2 price in the ETS. Research showed that a CO2 price of at least €50 is required to make CCS cost effective in Rotterdam. Currently, the CO2 price is around €25 (CE Delft, 2018a). By many, the deployment of blue hydrogen is described as a ‘transition phase’ for the development of large-scale green hydrogen utilization. The roadmap of this transition and the duration of this transition phase depend among other things on the cost reduction of green hydrogen and the pace of upscaling of the electrolysers and offshore wind farms. This uncertainty could decrease the willingness to invest in blue hydrogen. With a typical lifetime of 30 years for an SMR plant. Assumed that most plants will be constructed in the coming years, most plants will need to be replaced, regardless of alternatives, by 2050. This provides some insight on the role of blue hydrogen in the transition towards green hydrogen (Navigant, 2019).

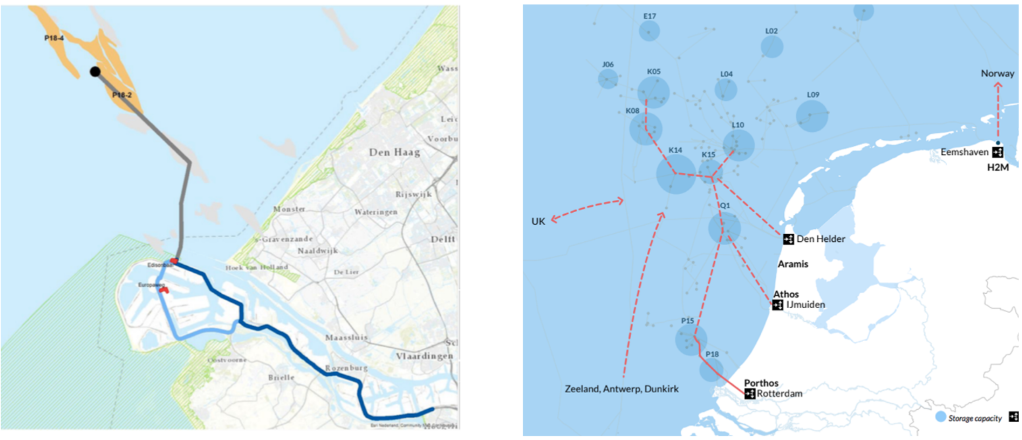


Figure 41: *Outlook of the Porthos infrastructure to store CO2 offshore and the available storage options at the North Sea (North Sea Energy, 2020; of Economic Affairs & Policy, 2019).*

In Rotterdam, Carbon Capture and Utilization (CCU) currently occurs in small volumes. The CO2 is captured during gasification in the industrial processes. After that, it is utilized in greenhouses in the region or as feedstock in other industrial processes. However, the volumes in this process are currently not significantly reducing emissions but they do improve the efficient use of the gasses in the system (of Economic Affairs & Policy, 2019). Since the capture rate is far from 100%, this hydrogen is 'grey', which means that the CO2 is not, or in minimal quantities, captured.

Offshore wind

As already mentioned above briefly, there are two ways in which offshore wind energy can supply electricity for the production of hydrogen. The first option is that the overshoot of electricity that is not required in the electricity grid is used to power the electrolysers. By doing this, the power-to-gas units serve as a flexibility mechanism. The second alternative is to operate dedicated offshore wind farms that are directly connected to the electrolysers located on the Maasvlakte conversion park. This is a favoured alternative in recent project announcements since it adheres to the required scale up of green hydrogen (Rijksoverheid, 2019). The currently installed offshore wind capacity at the North Sea is around 13 GW, of which 1 GW is located at the Dutch part of the sea (IEA, 2019b; Port of Rotterdam, n.d.). This Dutch capacity could be expanded to a maximum 60-70 GW, however the projected flow of hydrogen in Rotterdam, with Rotterdam as the hydrogen hub of North-West Europe requires a capacity of up to 200 GW. This restriction provides a playing field for two alternatives that can be implemented both (Port of Rotterdam, n.d.):

1. Interconnection with offshore grids of other countries located around the North Sea to create an offshore power hub and thereby increase the efficiency of the North Sea.
2. Import from other parts in the world where the potential benefits of renewable energy sources are higher, such as Northern Africa.

The potential output of the offshore wind farms is determined by the technology development of the wind turbines. Technology nowadays allows for a capacity factor of 29%, but this is expected to increase to up to 50% thanks to improvements in tower, blade and turbine size and, possibly, floating offshore wind farms (DNV GL, 2019). To make offshore wind farms financially attractive and to seal the business case, its output is sold by power purchase agreements. In these contracts, the government covers the 'losses' up to an agreed price if the electricity is not sold or sold below this price. In the future, the expected deals with hydrogen off-takers could solve this problem by creating a continuous demand for these wind farms. This opens up opportunities for chemical companies reliant on hydrogen feed-stocks to become co-investors in wind farms (ReNews, 2019). Connecting the offshore wind and hydrogen production can also be enforced by a so called blending obligation of the government to realise upscaling and cost reduction (Ministry of Economic Affairs and Climate Policy, 2020a).

Crucial for the future upscaling of offshore wind and the production costs of green hydrogen is the enhancement of the economics of offshore wind. Transmission costs should be decreased by economies of scale, supportive action by TenneT (grid operator) and innovation. The electricity price is expected to face downward development due to the increasing deployment of renewables and their low marginal costs. Therefore, capacity mechanisms may be required. Linking offshore wind directly to hydrogen may avoid the higher retail industry electricity prices and reduce the price by 60-80% in 2030 (IEA, 2019a).

The overview with a timeline is presented of all projects, both confirmed and expected, that are planned for the coming decades in the area of Rotterdam. This overview serves as background information for the information used in the analysis later on. It is primarily based on information derived from the 'Taskforce infrastructuur klimaatakkoord industrie', but is complemented with news announcements and other strategy reports (DNV GL, 2020). The transition where the research project is included is demarcated, but it experiences strong interrelations with many other projects.

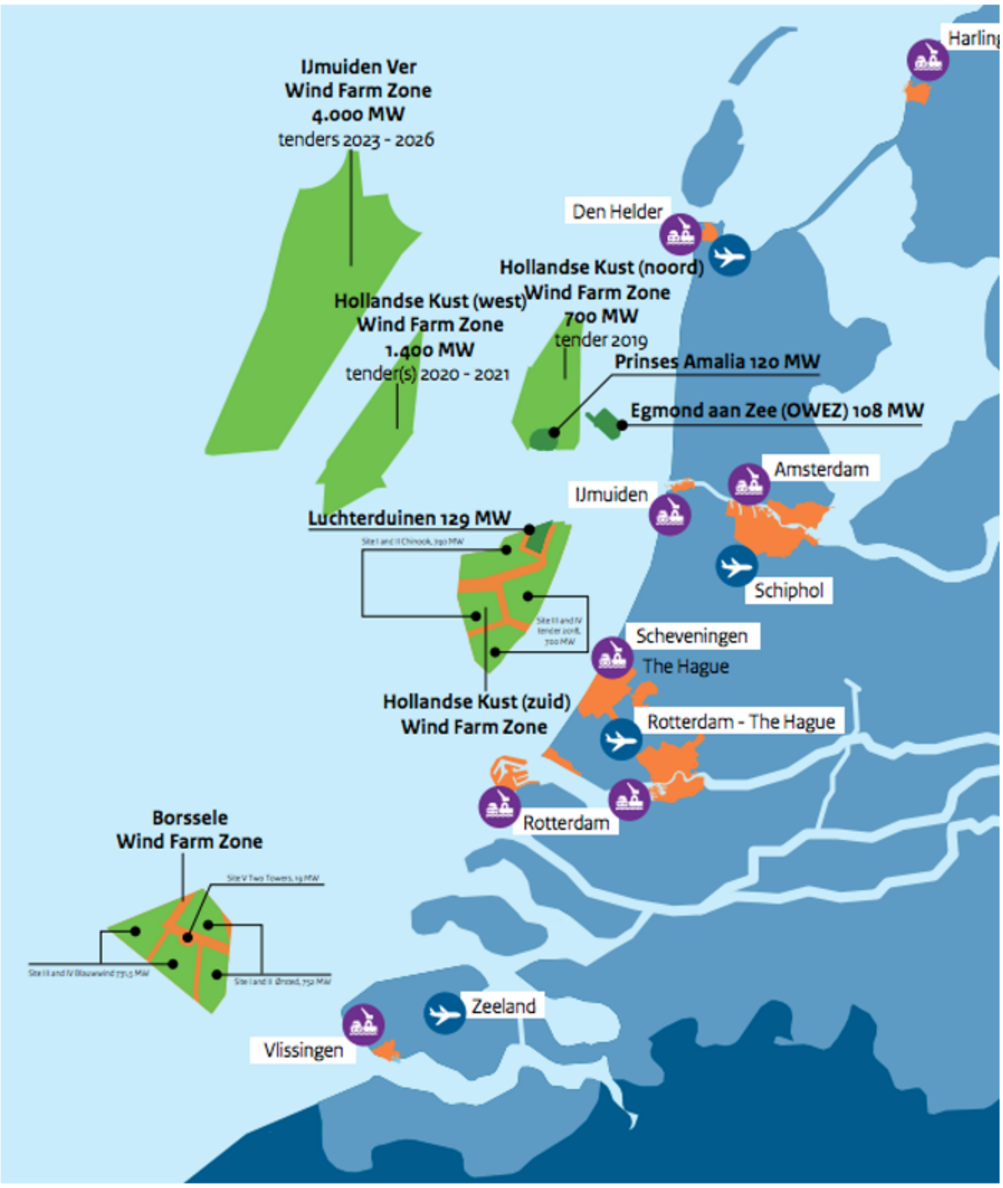


Figure 42: *Offshore wind development outlook for the coming years (Netherlands Enterprise Agency, 2018).*

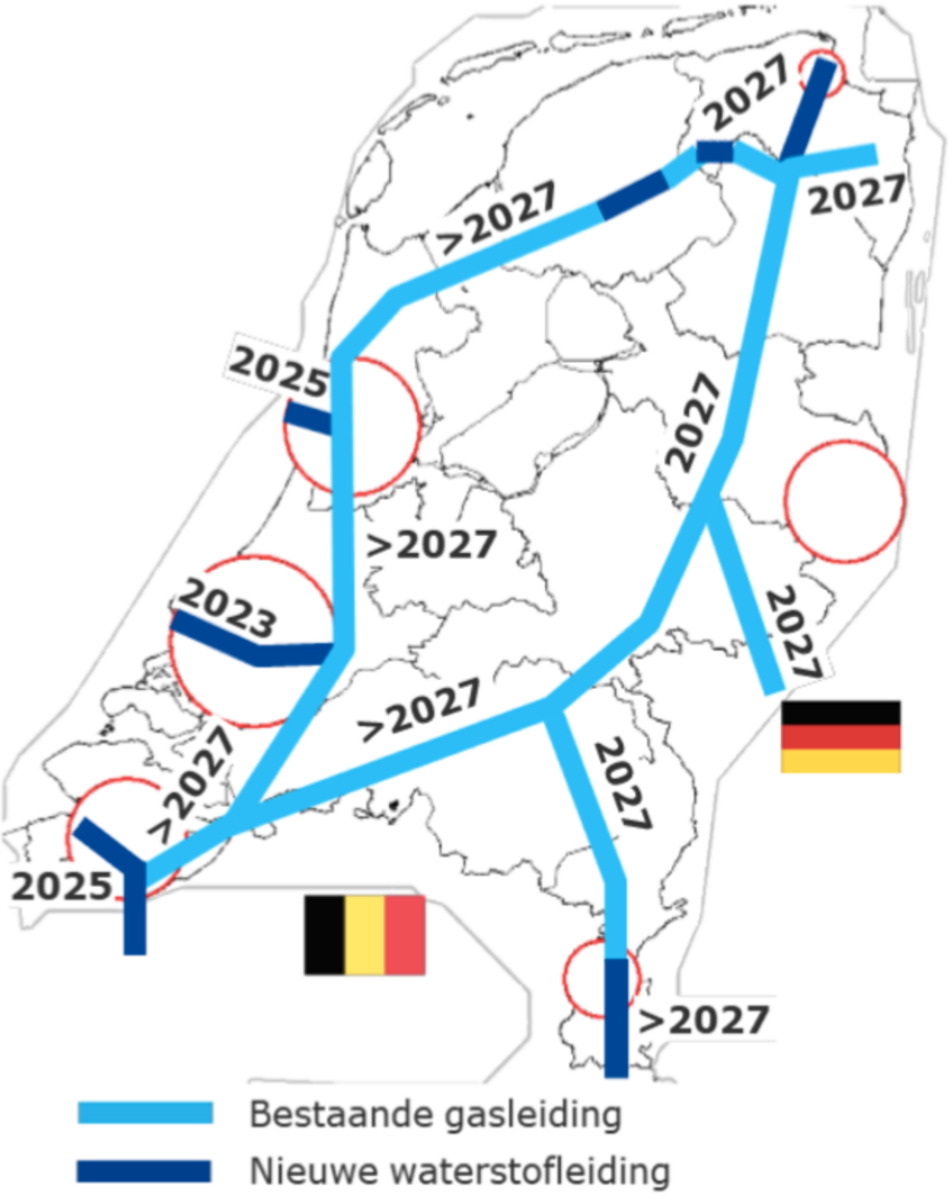


Figure 43: *Layout of the national hydrogen backbone in the Netherlands(DNV GL, 2020).*

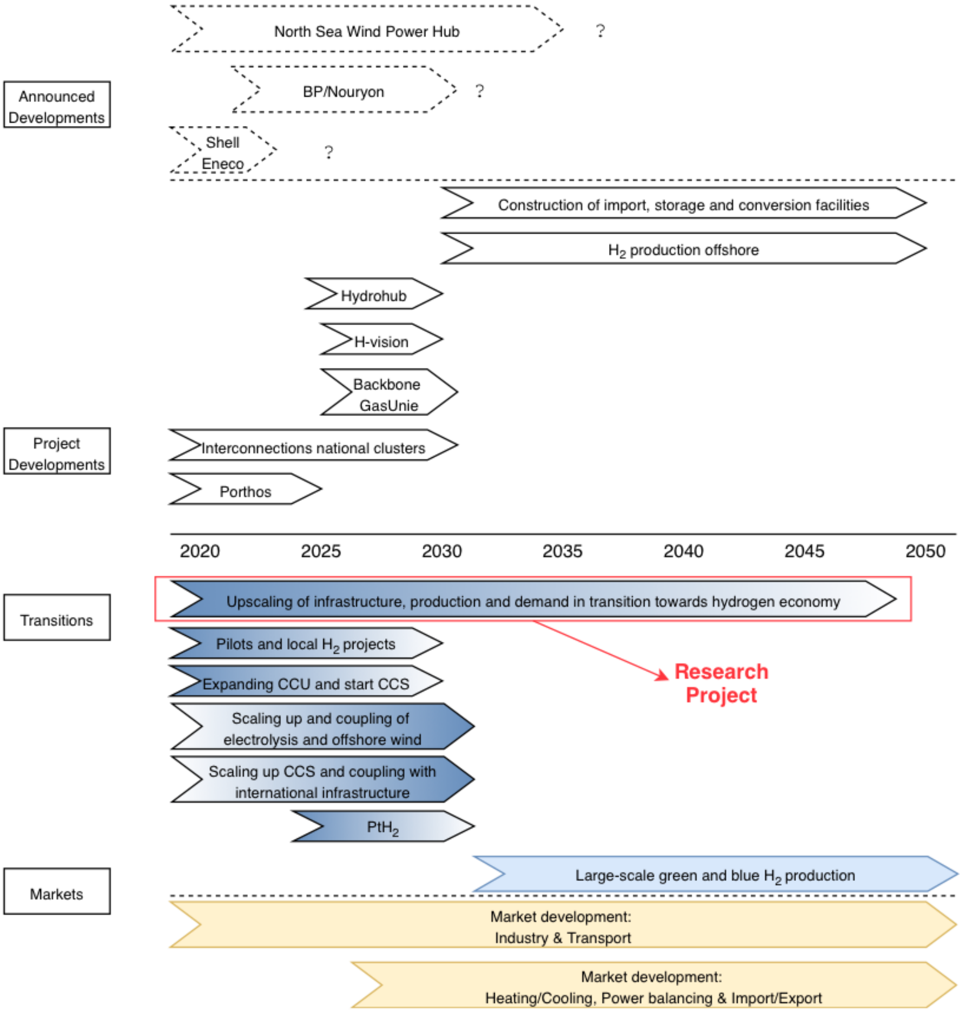


Figure 44: *Project development industrial cluster Rotterdam.*

Appendix D

Basic actor analysis

Existing actor regime

Task	**Actor types**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
Production by SMR and by-product	(Petro)Chemical companies, Oil refineries	Continuous flow of their H2 to end-consumers	To utilize their H2 and other residual gasses most efficiently and acquire extra income	Limited interconnection with demand centres; Low accessibility of network; Loss of quality assurance; Increase in complexity of regulation and standards.
CCU	OCAP	Interconnection between industries and integration of H2 infrastructure and CCU/CCS infrastructure	To effectively capture CO2 in industrial processes and utilize it elsewhere	No permission for storage underground; Lacking infrastructure for CCS; Volumes CCU not sufficient
Network operator/Hydrogen supplier	Air Products /Air Liquide	Interconnection between industries in PoR and North West Europe; market expansion, efficient utilization of production flows	To connect industry in PoR and neighbouring countries to provide them with low-cost good quality H2 and maintain security of supply	Interference in their well operating system; Quality standards could be violated; Uncertainty about role.
End-consumption	(Petro)Chemical companies, Oil refineries	Sufficient H_2 supply at reasonable cost price	To buy cheap H2 of required quality at desired time to enable industrial processes	No diversified supply mix; Dependence on limited H2 production as by-product

Task	Actor types	Interest	Objective	Perceived problems facing value chain transition

Table 18: *Actor descriptions of the current hydrogen system.*

Future actor regime

All actors of the new hydrogen value chain are divided in three different clusters based on relevance to research scope, and presented in the three tables:

1. Actors relevant for both end-situation and transition period with direct influence on and directly impacted by the development process
2. Actors relevant for the end situation and later stages of the transition period with indirect influence on and indirectly impacted by the development process
3. Actors relevant in the transition period with direct impact on development process, but whose role will diminish towards the end situation.

The actor roles as presented in the tables below are based on the expected end-situation. The next section on actor dynamics elaborates on the activities of actors in the transition period.

Task	Actor types	Major companies involved	Interest	Objective	Perceived problems facing value chain transition
Industrial hydrogen production	(Petro-) chemical companies, Oil refineries	Air Liquide, Air Products, OCI Nitrogen, Shell, BP, Nouryon, AkzoNobel	Maximum reachability for continuous flow of their H2	To utilize their H2 and other residual gasses most efficiently and maximize profit	H2 quality; Public vs private ownership of pipelines; Business case pipelines; Public systems integration
Reforming, Electrolysis	Petrochemical companies, chemical companies, oil refineries	Shell, Nouryon, BP, Other industrial companies	Expansion of nr and scale of demand centres to increase competitiveness of H2 with fossil carriers	To supply demand centres with blue/green H2 at any given time	Cost reduction; Full value chain integration; Private pipeline control; High-quality H2-market; System standards
Storage	Storage companies	Vopak, Gasunie, Eneco, Port of Rotterdam, Hydrogenious	Optimal utilization of storage potential in pipelines and salt caverns and integration with transportation system	To stabilize the volatile renewable energy production, cover peak demands and avoid congestion	Ownership infrastructure; Connectivity backbone with ICR; Geographical dependence storage

Task	**Actor types**	**Major companies involved**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
Distribution, Transmission	Network operators	Gasunie, Stedin	Alternative for gas-grid, optimization of high/low-pressure pipelines and use of existing assets	To provide stable supply of H_2 on national/regional level via an open network	Complexity full value chain development; Regulatory limitations of role; Dependency upscaling volumes; Open accessible network
Hydrogen demand	Industry	Ammonia industry, Oil refineries, (Petro-) Chemical companies, Fertilizer industry, Nouryon, Shell , BP, AkzoNobel, Other heating industry	Continuous flow of H2 for high-grade heat and possible feedstock as alternative for fossil gasses	To obtain a secure and cheap flow of H2 for heating and as feedstock.	Uncertainty system standards; Insufficient scale of supply; Need for two different H2 products; Cost reduction; Long-term policy consistency
	Mobility	Shell, BP, Air Liquide	Integration distribution/transmission infrastructure with refuelling infrastructure to support market development and match corresponding demand	To provide cost-effective fuel to decarbonize mobility sector and scale up H2 vehicles	Not gaining priority; Low market liquidity; Available electric alternatives; Low suitability for supply by pipeline; Dependency high purity
	Built environment	Essent, Eneco	Flow of low-grade heat to provide reliable alternative for natural gas and as source for district heating	To offer a decarbonized competitive alternative to natural gas for low-grade heat in the region	Available electric alternatives; High dependency on natural gas network; Demand volume is widespread; Dependence on government investments
Governance, Regulator	Ministries, Provinces	Ministry of Economic Affairs and Climate, Province of Zuid-Holland	Actualization of the policy goals, decarbonization of the energy system and economic development of PoR/Netherlands	To facilitate an integrated open H2 system while safeguarding public interest and committing to climate agreement	Uncertainty market sector development; No clear vision end-situation; Policy uncertainty around innovation; Long-term policies required

Task	**Actor types**	**Major companies involved**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
Regional Control	Public enterprises, Initiator, Facilitator, Investor	Port of Rotterdam	Decarbonization of the PoR while maintaining and improving economic position of the port nationally and internationally	To utilize the strategic position of the port as a hub for North-West Europe and to develop industrial activity by facilitating cooperation	Market development; Economic position; International dependency; Uncertainty upscaling; Spatial limitations; Long-term policy consistency; Cooperation system actors

Table 19: *System actors relevant for both end situation and transition period with direct influence on and directly impacted by the development process.*

Task	**Actor types**	**Major companies involved**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
Import	Energy companies	Equinor, GasTerra, Industrial companies, Port of Rotterdam	Development of market in PoR and PoR as national/international H_2 hub	To provide affordable H2 at moments of domestic supply shortage and to provide trade	Complexity different hydrogen forms; Pricing uncertainty; Conversion losses; Interconnections international infrastructure
Offshore wind	Offshore wind farm owners	BP, Essent, Eneco, Vattenfall, Ørsted	Development of reliable market to sell electricity overshoot and integrate H2 production with wind farms	To provide affordable, and high-volume resource for green H2 at any given time	Cost reduction uncertainty; Spatial limitations; Increasing demand volumes; Competitiveness international market; Green H2 demand
Trading	Utilities	GasTerra, Equinor, Industrial Companies	High-level interconnection between supply and demand centers; avoidance of congestion in grid	To maximize the difference between price of demand and supply	-

Task	**Actor types**	**Major companies involved**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
CC(U)S	Industrial producers	Network operators, Vopak, Ocap, Port of Rotterdam, Uniper, Engie	Technical optimization of capture, connection to storage under North Sea and utilization of existing assets	To maximize the capture rate of CO2, storage in-caverns and supply to agriculture and industry	Regulation on storage; Long-term policy consistency; Expected phase out of blue H2; Decentralized SMR production; Uncertainty systems purity standards
Hydrogen demand	Power supply	Uniper, EON	Reliable decarbonized energy carrier to meet peak demands in the electricity grid not supplied by renewable sources	To maintain security of supply on electricity grid by renewable energy sources	-
	Export	International energy companies	International H2 infrastructure where the PoR serves as a hub to rest of Europe	To sell the overshoot of H2 in the PoR and Dutch system for the best price to neighbouring regions	-

Table 20: *System actors relevant for the end situation and later stages of transition period with indirect influence on and indirectly impacted by the development process.*

Task	**Actor types**	**Major companies involved**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
Project developers	External consultancies	Royal HaskoningDHV, Berenschot, Kalavasta	Need for structuring of knowledge and project management on the H2 transition	To actualize an optimal H2 system	-
Technical research institutes	Knowledge institutes	Universities, ISPT, TNO, TKI, Wuppertal Institut, TU Delft	Need for technical feasibility studies in the H_2 transition	To actualize an optimal H2 system	Private/public organization structure

Task	**Actor types**	**Major companies involved**	**Interest**	**Objective**	**Perceived problems facing value chain transition**
Project managing	Independent supervisory institutes	EBN, 'Klimaattafels', Netbeheer Nederland, Deltalinqs	Actualization of the policy goals and decarbonization of the energy system	To bring together companies to actualize an integrated H2 system while safeguarding public interest	Cooperation system actors; Uncertainty system standards; Complexity hydrogen specifications; Market development; Long-term policy consistency

Table 21: *System actors being relevant just in the transition period. Their role will be expired in the end situation.*

Appendix E

Actor perspectives on visions and value chain

In the following tables, all actor perspectives are included, presenting the background for the decisions to be made for the construction of the visions (chapter 6) and the transition pathways (chapter 7). First, the actor perspectives affecting the visions are structured based on benefits and bottlenecks of the value chain elements for the future system. Subsequently, the actors' perspectives on the expected role of the value chain elements for both the transition period and the end-situation are summarized.

The second table constitutes the actor perspectives on the value chain dynamics presenting the interrelations of the elements and the relation of value chain elements to elements outside the value. The last column specifically elaborates on the relation between the different value chain elements and the pipeline transportation.

	Benefits in future system	**Bottlenecks in future system**	**Role in transition**	**Role end-situation**
SMR + CCS (Blue)	▪ Baseload production ▪ Minimal dependency on storage ▪ Utilization of not yet depreciated SMR units ▪ Netherlands favourable location and knowledge for CCS and natural gas supply ▪ Suitability for heating ▪ Providing scale for hydrogen market and infrastructure ▪ Storage CO_2 under North Sea is permitted	▪ Not optimal solution ▪ No full decarbonization since capture rate is 80-90% ▪ Low-purity limits allocation of flow ▪ PSA possibly required, if higher purity is desired for end-use or due to system standard ▪ Future competitiveness natural gas price in energy system ▪ Blue H2 attracts investments and momentum should have been assigned to green H2 ▪ Resource dependence on import ▪ Unclarity about responsibility of stored CO_2	▪ Upscaling of volumes for industry ▪ Especially role in private industrial network ▪ In combination with PSA, ability to cover full demand ▪ Natural gas price for industry is low, so low production costs ▪ Short-term reduction of CO2 emissions, which is overall goal of energy transition ▪ Develop transition location dependent; blue H2 in ICR in first phase ▪ Technological development of Blue H2 also just in take-off phase ▪ No consensus if blue H2 is strictly necessary in transition period ▪ CCS is expected to realize up to 50% of expected CO2 reduction in industry	▪ For heat in industry and/or built environment; replacement for natural gas ▪ Preferably phased out, but no clear consensus ▪ The active role depends on demand from refineries and other large industry ▪ Possibly, in combination with PSA, utilized in all sectors ▪ If CCS is applied in end-situation, SMR requires centralised operation
Electrolysis (Green	▪ High purity ▪ Suitable for mobility and as industrial feedstock ▪ Low marginal costs of renewables ▪ Could be fully decarbonized ▪ Centralised electrolyser park (Maasvlakte) enables benefits from economies of scale	▪ - Problems regarding baseload demand and volatile production ▪ Necessary alignment with renewable electricity generation ▪ Upscaling technology and volumes determined by international market ▪ Spatial limitations North Sea ▪ Problems regarding supply sufficient scale ▪ Storage required as volumes increase ▪ Long-term process development; construction and operation of electrolysers	▪ Not feasible on short-term in sufficient volumes ▪ Utilization in short term could cause increase of fossil resources for electricity mix ▪ Increasing volumes require connection to national backbone for storage in salt caverns ▪ Utilization for heat is 'waste' of pure H_2 ▪ Develop transition location dependent, green H_2 not most suitable for ICR in first phase ▪ Possibly inevitable to blend with blue H_2 in coming years to increase volumes and reduce complexity of transportation	▪ Flexibility function for electricity overshoots ▪ Dependent on costs of H2 import ▪ Uncertainty regarding feasibility and necessity of domestic production ▪ Preferred dominant supplier of hydrogen ▪ Utilization as chemical product ▪ After sufficient upscaling and cost reduction, it could also be utilized for heating ▪ Strong dependency on future investments and competitiveness of renewables with low marginal costs

	Benefits in future system	Bottlenecks in future system	Role in transition	Role end-situation
Industrial by-product	▪ Residual stream of hydrogen will always exist ▪ Highest purity ▪ Efficient utilization of rest streams ▪ Already existing system, reduced complexity without multi-actors	▪ Existing privatised network could be outcompeted by public network ▪ Production volumes are negligible compared to expected demands ▪ CCS at existing processes does not allow for very high capture rates	▪ Volumes too low to play a role in transition period ▪ Transportation organized in privately owned and operated point-to-point pipelines	▪ Could operate own infrastructure next to new hydrogen system ▪ Role in total hydrogen system will be limited, but for industrial companies useful
Conversion	▪ Liquefaction, ammonia and LOHC enable different forms of transport; shipping and tube trailers ▪ Enables also small-scale and short-term liquefied storage	▪ Expensive conversion terminals and high operating costs ▪ LH_2 is much more complex than LNG ▪ Every conversion step has significant energy consumption and impact on purity/quality of H_2 ▪ Maintaining liquid state has significant energy consumption (cooling)	▪ Import is expected to develop on the middle- to long-term 2035-2040 ▪ Depends on development of international market ▪ Technologically still far from mature	▪ Necessary element to deploy the full range hydrogen system optimally ▪ Conversion steps should be minimized ▪ Decentralised or centralised conversion (before or after transport) depends on type of production, transport and demand
PSA	▪ Could be applied anywhere in the system on centralised large-scale or decentralised small-scale	▪ High purification costs, but expected to decline with technological development ▪ Downstream separation of PSA perceived to be too expensive	▪ Role in transition period depends on utilization of blue H_2 and corresponding demand in feedstock industry and mobility demand	▪ Preferably a minimized role since this will mean that green H_2 has developed sufficient volumes to supply also heat industry and that blue H_2 is phased out ▪ Its role depends on type of import and loss of quality during transportation
Storage	▪ Large-scale seasonal storage (salt caverns) and small-scale storage to deal with variations (linepacking) feasible ▪ Provides flexibility for which hydrogen is used ▪ Adjustments required are feasible, but not easy ▪ Good connection to national backbone	▪ Locational dependence ▪ Location in Groningen is ideal for natural gas system, but not very suitable for hydrogen system since this should be oriented towards Ruhr-area ▪ Natural gas still needs reserves and utilization of salt caverns, especially considering the expected stop of Dutch gas ▪ LH_2 storage is energy-intensive and has possible impact on purity of hydrogen	▪ Groningen salt caverns are required for natural gas at least on the short-term ▪ On the short-term majority of required storage capacity can be provided by linepacking, but on long-term salt caverns needed ▪ Role of storage in early stages of transition is expected to be low. Role for storage operators when system approaches volumes of current natural gas system ▪ Development salt caverns responsibility of network operator	▪ Salt cavern storage in Groningen is desired by public enterprises and exploiters of the fields ▪ Salt caverns in direction of Ruhr-area are more available and have a more suitable location for the hydrogen network ▪ In end-situation, actor roles regarding storage are expected to be similar to current natural gas system

	Benefits in future system	**Bottlenecks in future system**	**Role in transition**	**Role end-situation**
Pipeline network general	▪ Suitable for long-distance transport ▪ Pipeline transport preferred for import over land ▪ Suitable for high volumes ▪ System standards in pipelines of PoR as transit port should align with H_2 state in import	▪ Higher complexity than natural gas network ▪ Lower density and energy density of hydrogen increases complexity with low-purity transport or blending	▪ Full high-purity national backbone is unfeasible in the short and middle-term ▪ Current privatized network is not sufficient in volume to operate future expected demand	▪ Mobility sector attracts tube trailers as transportation mean ▪ Open accessible network with clear tariffs is required
Blending	▪ Could be theoretically feasible in network with only burning appliances ▪ Stimulating supply development by guaranteed extraction ▪ With choosing the right limit, investment costs on short-term could be low	▪ Difficulty in multi-phase adjustment process of end-use appliances ▪ Difficulty in monitoring and billing of the extraction of gas from the network due to different caloric values of NG and H_2 ▪ Accompanied with separation plants increases costs ▪ Blending green H_2 is waste of purity ▪ Increased complexity due to ranges Wobbe-index ▪ Very low suitability in combination with import ▪ Varying percentage of H_2 in real-time can damage appliances with burners designed for specific gas composition ▪ Increasing blending limit over the years is highly inappropriate for appliances ▪ Quality of gas cannot be guaranteed due to lower burning value H_2	▪ Volumes of H_2 in the blend are too low to contribute to upscaling of infrastructure and market ▪ There are no policy plans to increase blending limits ▪ Virtual blending is feasible. Physical separation of the gasses, but virtually contribution to green H_2 obliged ▪ Could be functioning as sink for demand on the short-term ▪ As transition mean, blending has too large impact on general functioning of system	▪ Expected demand volumes exceed blending capacities ▪ All investments in blending are not contributing to the real solution ▪ Perceived as infeasible and not desired alternative in end-situation
Reuse existing network	▪ Current natural gas network exists of bundles of parallel pipelines, of which parts can be made available up until the furthest corners of the network ▪ Large volumes of existing infrastructure are required if H_2 is supposed to fulfil flexibility function of natural gas ▪ Economic value of existing network is preserved	▪ Insufficient availability of existing pipelines ▪ High geographical dependency (layout of natural gas network is not favourable for future hydrogen system) ▪ Presence of demand and supply should determine pipeline development, not location of existing pipeline, wrong incentive	▪ Methane consumption in industrial clusters is still significant for short- and middle-term, which decreases availability of pipelines ▪ Natural gas network typically has larger volume pipelines. H_2 production is insufficient in short- and middle-term to fill up cushion gas ▪ Closing of Dutch gas fields and decarbonization of energy flow should increase availability of pipelines	▪ Low or high purity H_2 transportation no impact on suitability of reusing existing network, adjustments to existing network are needed and feasible ▪ Favoured alternative in long-term ▪ Electrification in demand sectors increases availability of pipelines

	Benefits in future system	**Bottlenecks in future system**	**Role in transition**	**Role end-situation**
Dedicated network	▪ Construction of dedicated pipelines can be 100% aligned to location of supply and demand development; this is the right causal sequence ▪ Least complicated alternative	▪ High capital costs ▪ Possible double infrastructure in the end-situation	▪ Could serve at crucial locations that require pipeline transport in the short-term where waiting for possible reuse is not possible ▪ Alignment with future plans of reusing existing network is preferred ▪ Preferred by industrial companies to speed up development due to low dependence on external factors	▪ Vision end-situation and level of deployment of dedicated pipelines depends on feasibility of reusing existing infrastructure ▪ Reuse is applied where possible, dedicated is first alternative
Industrial demand	▪ Expected base load demand, large volumes with limited amount of connections ▪ High investment capacity ▪ Only sector with guaranteed demand; interesting for business case ▪ Industry has direct connection to high-pressure transmission grid	▪ Expensive adjustment to heaters and other end-use appliances ▪ Long depreciation period and capital costs of appliances requires consistent policies to avoid situation currently experienced with coal and biomass gasification ▪ Difficult adjustment and specifications of end-use appliances makes it unsuitable for blending ▪ Profitable business case is essential; industry is a price sensitive market. ▪ Levels of demand will exceed possible production capacities on short-term, this could create a sink with guaranteed demand for both green and blue H_2 ▪ Utilization and cost reduction of green H_2 in industry is expected to incentivize industry to adjust processes to be suitable for hydrogen production ▪ Sector exhibits scale and required elements to enable start of transition	▪ H2 demand development largely dependent on electrification and general system development ▪ Industry desires to be located near source of energy (reason of settling in NL with NG), large-scale source of H_2 not expected in NL so could cause migration of industry, which means a decrease in H_2 demand	

	Benefits in future system	**Bottlenecks in future system**	**Role in transition**	**Role end-situation**
Mobility demand	▪ Heavy duty transport, aviation and shipping sector have no or few other alternatives ▪ Progress is more significant and observable thanks to smaller demand volumes than in industry, which increases interest as market for high-purity H_2	▪ Traditional business of network operators is in heat sector, so they could determine to not prioritize mobility sector ▪ In mobility sector, stronger role is determined for BEV's, also for heavy-duty ▪ FCEV-technology not mature and high costs ▪ Volumes are not significant and sector is hard to abate	▪ Focus on tube trailers as transport alternative ▪ H_2 transport over road is immature technology, also in terms of ability to deal with required volumes ▪ Sector is expected to benefit from upscaling in industry, but cannot provide fundament to stimulate hydrogen transition	▪ The industry can serve in the first years as sink for high-purity H_2 and once the mobility market starts to develop supply can be allocated to this sector ▪ No consensus on necessity of pipeline infrastructure ▪ Role in end-situation has large dependence on technological development on FCEV's, BEV's, LH_2 road transport and policy
Built environment demand	▪ Although widespread over many end-consumers, the total expected sectoral demand is very high (can double current H_2 market) ▪ Regional pipeline network is developed in ring structures, so adjustments can be made without much hazards ▪ Decentral investment power is high, less reliance on business case and shareholders ▪ Small-scale adjustments to end-use appliances are easy to accomplish ▪ Built environment is not price sensitive, no possibility to move, willingness to pay for comfort (H_2 more comfortable than heat pumps, district heating etc.	▪ High seasonal variations in demand ▪ Network operators tend to have more focus on industry, which is connected to high-transmission grid, has fewer connections and is closer to production of H_2 ▪ Quantity of end-use appliances with adjustments ▪ Finely meshed network with many connections is not ideal situation to start complex process ▪ Production is controlled by industrial sector ▪ High dependency on active role government	▪ H_2 in built environment can play role thanks to low transportation costs; there is more than efficiency ▪ Potential is underestimated, extreme seasonal variations require molecules next to electrification; reduce, electrify and complement with H_2 ▪ No significant development expected on short-term ▪ Possibly decentralised fuel cells for local industry located outside industrial clusters	▪ With development of the H_2 market in built environment more certainty can be created, more markets give more certainty ▪ Role of H_2 as molecule energy carrier next to electrification ▪ Level of deployment depends on level of reduction of energy use and electrification ▪ Few other alternatives as molecular energy carrier, so role in end-situation is expected
Import, Export	▪ Self-sufficiency for the Netherlands is infeasible (current energy import is already over 50%) ▪ Import/export is needed to maintain economic position of PoR and Netherlands	▪ No consensus if imported hydrogen as LH_2 is suitable for transport over long distances; this is of high importance to level of import in PoR ▪ Netherlands not expected to reach net export on a yearly base	▪ On short- to middle-term not expected due to required technological development and not existing or immature international market ▪ Upscaling and cost-reduction of technologies will be realized at international market	▪ On long-term international market is required to develop liquidity and security of supply ▪ On long-term all beneficial aspects of H_2 can be fully deployed at international market

Table 22: *Actor perspectives affecting the strategies and actions at visions level.*

	Relation to value chain elements	**Relation to elements outside value chain**	**Relation to pipeline network**
SMR + CCS (Blue)	▪ SMR is able to produce the volumes that industry and the hydrogen market in general desire if upscaling is targeted ▪ Blue H2 is to be used in sectors with large heating demand volumes (industry, built environment) or combined with PSA in other sectors ▪ CCS required ▪ No dependency on storage ▪ No dependency on RE ▪ Resource dependence (natural gas) on import	▪ Many not yet depreciated natural gas appliances in industry ▪ Natural gas price for industry is much lower than in built environment, which makes SMR interesting for industry (6-7 ct/m3 vs 70-80 ct/m3) ▪ No consensus if policy mechanisms are required to phase out blue as transition period moves on and green H2 starts scaling up	▪ Dedicated (privatised) pipelines in industry for transportation of blue H2 ▪ Blending with natural gas is inefficient and expensive in combination with PSA ▪ In existing pipelines feasible since blue H2 serves as replacement natural gas ▪ Dependence on purity standard in network ▪ Not applicable to currently operated (high-purity) private industrial network
Electrolysis (Green)	▪ High purity H2 from electrolysis suitable as feedstock and for fuel cells ▪ Electrolysis design often directly linked to industrial consumers to guarantee H2 demand for business case ▪ Uncertainty around H2 demand development in mobility sector (fuel cells) ▪ Low volumes in short-term preferred to sectors with reasonable demand to obtain most impact (mobility) ▪ Require storage as volumes increase ▪ High dependence on electricity supply	▪ Operating GW-scale at baseload requires dramatic amount of electricity ▪ Cycle-effectiveness of deploying green H2 as sustainable energy carrier highly depends on decarbonization electricity mix ▪ Alignment to offshore wind capacity is essential ▪ Functioning in combination with storage as flexibility for electricity system ▪ Developing scale, cost reduction and efficiency increase required	▪ Injection into existing private network operating on high-purity could be feasible ▪ Possible injection into dedicated pipelines with blue H2 for industry, although it is a waste of purity ▪ Volatile production requires storage and connection to national backbone to reach salt caverns ▪ In existing pipelines not very feasible on short-term, highly dependent on location and NG demand ▪ Transportation in pipelines becomes interesting when volumes increase, due to large pipeline volumes and cushion gas
Industrial by-product	▪ Industrial residual stream is operated by industry and possibly connected to mobility sector in which industry also has a stake	▪ Rest stream fully integrates with steam production, ammonia production and chlor-alkaline production	▪ Transportation of private industrial pipelines not willingly towards connection with public system ▪ Small existing pipelines not suitable for future expected demands ▪ Could be operated in separate infrastructure next to new hydrogen system

	Relation to value chain elements	Relation to elements outside value chain	Relation to pipeline network
Conversion	▪ Strong relation to import since H2 is expected to be imported in multiple varying forms; LH2, Ammonia, GH2 and LOHC ▪ Conversion possibly needed for liquified storage but very uncertain	▪ Strong relation to import increases relevance for PoR as transit port ▪ Optimize alignment with other system elements to minimize conversion steps ▪ Costs, efficiency and impact on purity require optimisation	▪ To avoid unnecessary conversion, transport and consumption in the state of delivery is preferred, i.e. LH2 in tube trailers to mobility and ammonia to industry ▪ Preferred type of transport depends on losses and economics
PSA	▪ Possible important role in system as key link between green and blue H2 system ▪ Specification of end-use appliances and system standard determine level of small-scale utilization down-stream	▪ High uncertainty regarding utilization of PSA due to its dependence on the combination of elements in the future value chain ▪ Economics will determine if PSA is applied large-scale centralised (after SMR) or small-scale decentralised (at end-use site)	▪ Network operator determines standards of network and requirements for gas; no consensus on responsibility for required purification steps
Storage	▪ Industrial sector is not dependent on storage in current contracted hydrogen trade with continuous flow ▪ Storage not required for blue H2 system because of baseload production ▪ Storage required for green H2 with volatile production ▪ Demands in industry exceed supply so storage not necessary requirement in short term	▪ Storage in salt caverns most economically feasible option ▪ Volumes of NG and required storage in coming years for NG determine availability of salt caverns for H2 ▪ Feasibility of liquified above ground storage uncertain due to energy losses and costs ▪ Storage required if H2 is to be used for flexibility in electricity system	▪ The salt caverns in Groningen are a dominant factor in the strategy to utilize the national backbone, although their locations are not ideal ▪ Salt caverns need to be adjusted to the system standards in the national backbone ▪ Line-packing in pipelines will provide enough storage capacity in coming years, where production volumes will be low ▪ Pipelines towards Ruhr-area (with salt caverns) more effective based on location
Pipeline network general	▪ Depends on state/form and purpose of H2 ▪ Construction of pipelines should be based on presence of supply and demand, not on location of (existing) pipelines	▪ Possibly two networks operated with different purities ▪ Construction in bundles with other chemical pipelines is preferred ▪ Industry desires to self-manage crucial pipelines ▪ No consensus about purity standard (or multiple standards) in network (green or blue) ▪ Transition to H2 pipelines should be integrated in the natural gas transition from low-caloric to high-caloric gas	-

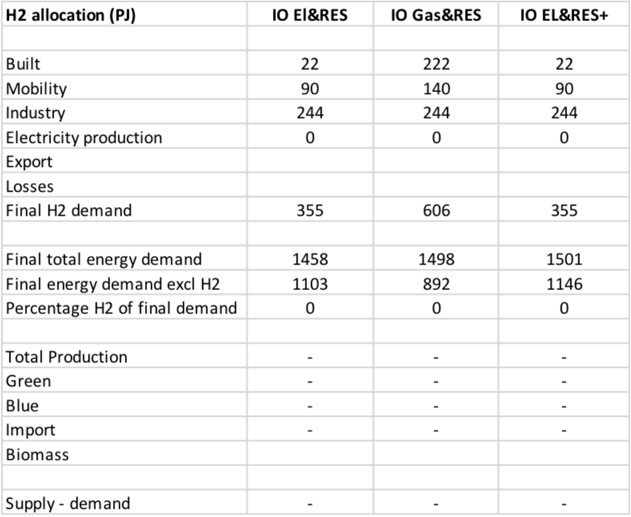
	Relation to value chain elements	**Relation to elements outside value chain**	**Relation to pipeline network**
Blending	▪ High dependency on decentralised PSA at end-consumption site ▪ Large consequences for complexity of adjustment of end-use appliances ▪ Could be viable with blue H2, but very unfavourable for green H2	▪ Quantity of H2 in blend is dependent on seasonal variations in RE production (in summer high), average is a few % but possible bulks of up to 100% H2 ▪ Maintains a specific role for and dependency on large volumes of NG; so dependency on import	-
Reuse existing network	▪ Suitable for all types of H2 ▪ Explicit suitable for transportation in built environment, although it will be a complex transition and dependent on whether supply will be allocated to the built environment	▪ Location of backbone in NL not ideal for H2 (North-East to South-West, while West to South-East is preferred) ▪ Align plans to readiness of backbone in 2026 ▪ Reuse of existing pipelines in built environment heavily dependent on active role of government, province and municipalities to incentivize citizens ▪ Economically often most effective alternative ▪ Strong dependency on decrease of NG demand/supply	-
Dedicated network	▪ Suitable for all types of H2 ▪ Already started to be deployed for H2 transport in industry (both private and public) ▪ Strong relation to guaranteed demand, which is only the case in industry ▪ Would be required alternative in mobility sector due to absence of existing pipelines	▪ For storage, connection to the national backbone is required ▪ If connected to continuous flow of import, storage not required ▪ Methane consumption in industrial clusters expected to be too high in short- and middle-term to reuse existing infra ▪ Lowest dependence on other uncertain factors, i.e. technical feasibility, policy, standards, especially when privately operated	-
Industrial demand	▪ Feedstock industry requires high-purity, but heating low-purity H2 ▪ Alignment with H2 stream as residual gas required ▪ Industry has direct connection to both electrolysers and SMR facilities ▪ Industry is directly connected to high-pressure transmission grid	▪ Low price of natural gas and high heat demand for industry increase interest in blue H2 ▪ Possible utilization of electric boilers for high-grade heat could decrease demand, but not mature technology yet ▪ Not many alternatives for decarbonized high-grade heat ▪ High-level integration with cycles of other chemical products	▪ Preference for privatised pipelines for first initiated projects ▪ Electrolysers constructed in industrial clusters minimize need for transport ▪ Dedicated electrolysers for refineries increase interest in point-to-point pipelines ▪ High NG demand in coming years cause deployment of existing grid for NG

	Relation to value chain elements	**Relation to elements outside value chain**	**Relation to pipeline network**
Mobility demand	▪ Fuel cells in mobility sector require high-purity H2 ▪ H2 mobility sector is closely interwoven with industrial companies, due to common ownership	▪ Strong alignment with electrification of the sector, i.e. BEV's ▪ Strong interdependence with rolling out of the refuelling infrastructure, which increases reliance on policy mechanism to incentivize mobility market ▪ Very low consensus on whether mobility sector is expected to develop in het short- to middle-term	▪ Mobility sector never had a pipeline infrastructure, although gasoline market has large volumes, contradiction whether this is needed now ▪ Development of demand in shipping and aviation sector have small influence on fundamentals of pipeline infrastructure ▪ Expected reliance on tube trailers
Built environment	▪ Built environment require low-purity H2 for heating appliances ▪ Large dependency on storage due to high variations in demand ▪ Utilization of H2 in district heating is infeasible, expensive and significant conversion and transportation losses	▪ Strong dependence on active role of government to incentivize citizens ▪ Complex situation for local industry desiring high-grade heat, but are located in built environment outside sectoral industrial clusters ▪ Strong dependence on level of electrification, H2 will support electricity in built environment	▪ Low infrastructure costs in built environment ▪ High supply of green H2 in summer and high demand for low-grade heat in winter determines unsuitability for blending, appliances require consistency in gas content ▪ High applicability for reuse NG infrastructure
Import, Export	▪ Both import and export are expected to be dominated by high-purity H2 ▪ Import and export are specifically dependent on each other since PoR is expected to serve as transit port and the Netherlands as transit country ▪ National H2 will never reach the volumes to contribute to export	▪ Ruhr-area for which PoR serves as transit port also requires pure H2 ▪ Cost reduction of import could decrease necessity for offshore wind and electrolyser development ▪ The level of import fully depends on economics; the transportation and conversion costs and losses should justify the difference in cost price ▪ The connection to the international market will predominantly determine liquidity, upscaling and cost reduction that is to be experienced in the Netherlands	▪ Natural gas pipelines through Italy and Spain can organize GH2 import ▪ Imported GH2 is directly suitable without conversion to be inserted in local pipeline network, but dependent on network standards ▪ Imported H2 not suitable for blending

Table 23: *Actor perspectives on systems outlook and dynamics value chain elements.*

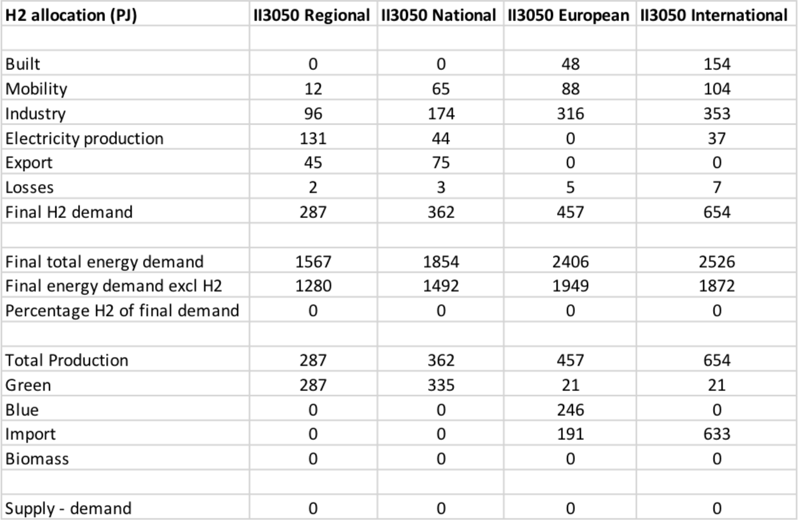
Appendix F

Background data scenario reports



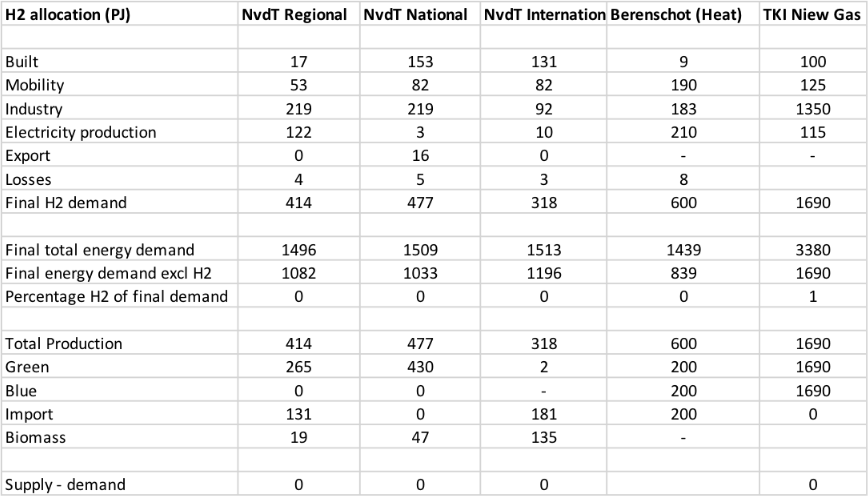
H2 allocation (PJ)	IO El&RES	IO Gas&RES	IO EL&RES+
Built	22	222	22
Mobility	90	140	90
Industry	244	244	244
Electricity production	0	0	0
Export			
Losses			
Final H2 demand	355	606	355
Final total energy demand	1458	1498	1501
Final energy demand excl H2	1103	892	1146
Percentage H2 of final demand	0	0	0
Total Production	-	-	-
Green	-	-	-
Blue	-	-	-
Import	-	-	-
Biomass			
Supply - demand	-	-	-

Figure 45: *Background data Infrastructure Outlook scenarios.*



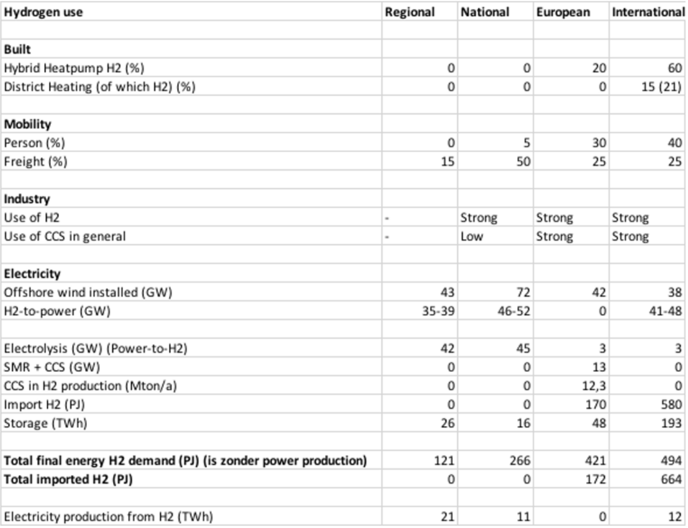
H2 allocation (PJ)	II3050 Regional	II3050 National	II3050 European	II3050 International
Built	0	0	48	154
Mobility	12	65	88	104
Industry	96	174	316	353
Electricity production	131	44	0	37
Export	45	75	0	0
Losses	2	3	5	7
Final H2 demand	287	362	457	654
Final total energy demand	1567	1854	2406	2526
Final energy demand excl H2	1280	1492	1949	1872
Percentage H2 of final demand	0	0	0	0
Total Production	287	362	457	654
Green	287	335	21	21
Blue	0	0	246	0
Import	0	0	191	633
Biomass	0	0	0	0
Supply - demand	0	0	0	0

Figure 46: *Background data II3050 scenarios.*



H2 allocation (PJ)	NvdT Regional	NvdT National	NvdT Internation	Berenschot (Heat)	TKI Niew Gas
Built	17	153	131	9	100
Mobility	53	82	82	190	125
Industry	219	219	92	183	1350
Electricity production	122	3	10	210	115
Export	0	16	0	-	-
Losses	4	5	3	8	
Final H2 demand	414	477	318	600	1690
Final total energy demand	1496	1509	1513	1439	3380
Final energy demand excl H2	1082	1033	1196	839	1690
Percentage H2 of final demand	0	0	0	0	1
Total Production	414	477	318	600	1690
Green	265	430	2	200	1690
Blue	0	0	-	200	1690
Import	131	0	181	200	0
Biomass	19	47	135	-	
Supply - demand	0	0	0		0

Figure 47: *Background data NvdT, Berenschot Heat and TKI Nieuw gas scenarios.*



Hydrogen use	**Regional**	**National**	**European**	**International**
Built				
Hybrid Heatpump H2 (%)	0	0	20	60
District Heating (of which H2) (%)	0	0	0	15 (21)
Mobility				
Person (%)	0	5	30	40
Freight (%)	15	50	25	25
Industry				
Use of H2	-	Strong	Strong	Strong
Use of CCS in general	-	Low	Strong	Strong
Electricity				
Offshore wind installed (GW)	43	72	42	38
H2-to-power (GW)	35-39	46-52	0	41-48
Electrolysis (GW) (Power-to-H2)	42	45	3	3
SMR + CCS (GW)	0	0	13	0
CCS in H2 production (Mton/a)	0	0	12,3	0
Import H2 (PJ)	0	0	170	580
Storage (TWh)	26	16	48	193
Total final energy H2 demand (PJ) (is zonder power production)	121	266	421	494
Total imported H2 (PJ)	0	0	172	664
Electricity production from H2 (TWh)	21	11	0	12

Figure 48: *Installed capacities in II3050 scenarios.*

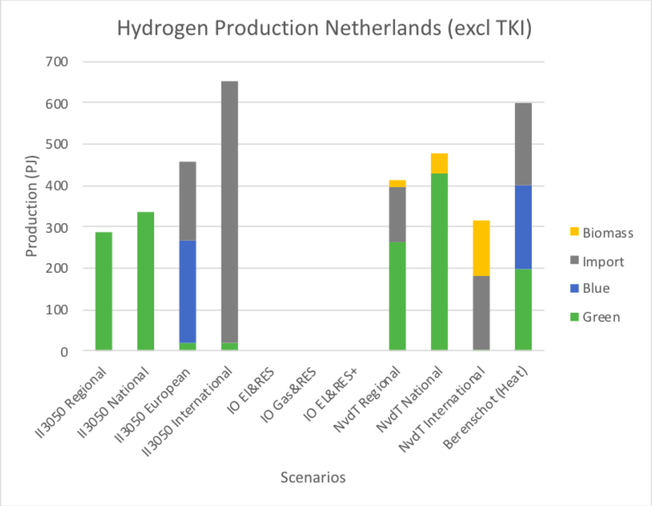


Figure 49: *Hydrogen production in the Netherlands excluding the TKI Nieuw Gas scenario.*

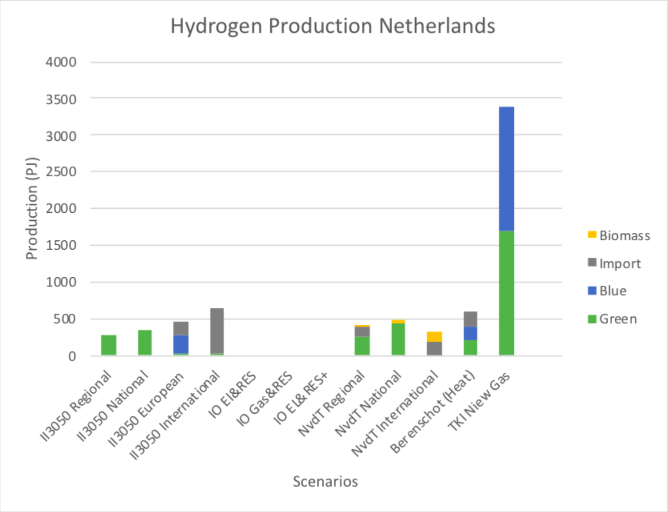


Figure 50: *Hydrogen production in the Netherlands including the TKI Nieuw Gas scenario.*

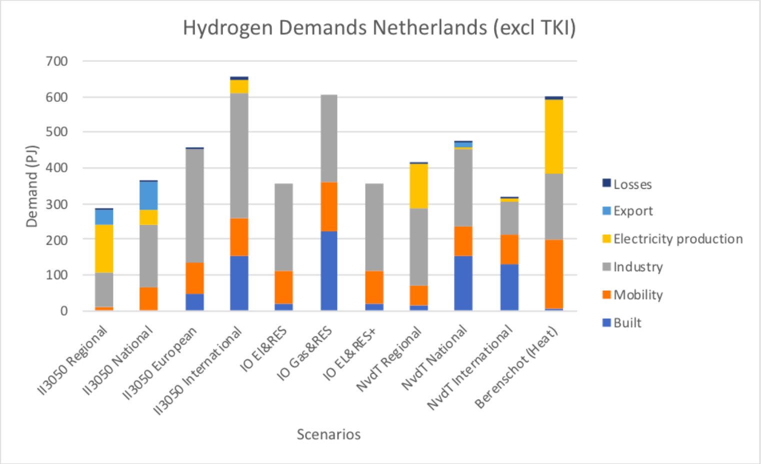


Figure 51: *Hydrogen demand in the Netherlands excluding the TKI Nieuw Gas scenario.*

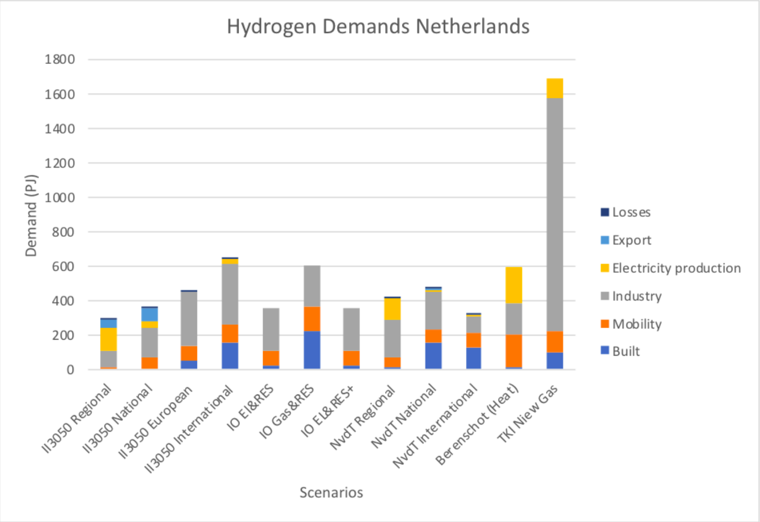


Figure 52: *Hydrogen demand in the Netherlands including the TKI Nieuw Gas scenario.*

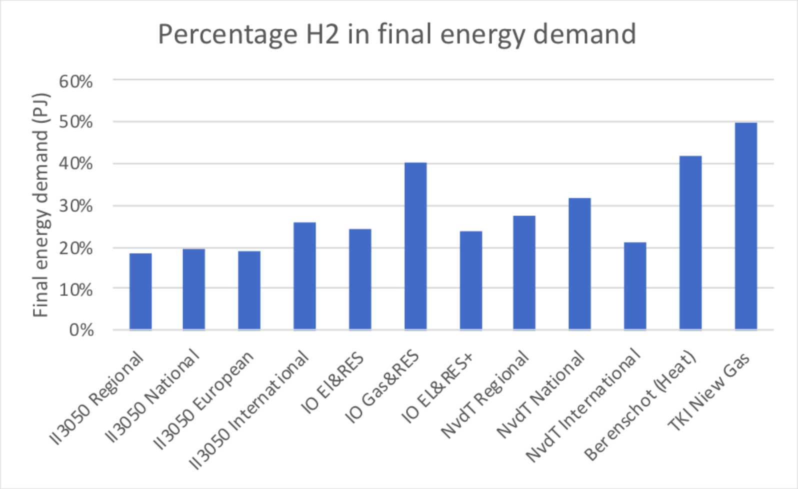


Figure 53: *The share of hydrogen in the final energy demand as determined in the Netherlands for all scenario reports.*

Appendix G

Assumptions for end-visions

The ETM enables the researcher to set, among other elements, **installed capacities for offshore wind and for electrolysis**. From the system development perspective, it is important to let these capacities increase interdependently. Assumed here is that offshore wind capacity is roughly two times the electrolyser capacity needed. This is extracted from future perspectives described by the Port of Rotterdam (Port of Rotterdam, 2020b). In the visions, the electrolysis capacity is proportionally a little higher, because of excess electricity of the general electricity mix that is being supplied to the electrolysers next to the electricity from offshore wind.

Green hydrogen is predetermined a prominent role in all scenarios for 2050 although the route towards the utilization of green hydrogen in 2050 varies. Therefore, all visions describe a significant contribution of green hydrogen in 2050. Also, the imported hydrogen is expected to be mainly green. In no pathway, green hydrogen is expected to fulfil the total hydrogen demand on itself, so the supply mix is diversified.

All visions exhibit a **diversified hydrogen supply mix**. By this diversity, the dependence on solely import or one production sector is avoided. Furthermore, the Dutch capacity for green hydrogen production is assumed to be insufficient to supply the demands presented in the pathways. Due to recent developments and increased interest in hydrogen, the expected demands are higher than in scenario reports presented a few years ago. On the other hand, it can be argued whether it is cost-effective to supply full demand by green hydrogen.

Biomass gasification for the production of hydrogen is no role determined in the visions. The NvdT scenarios included this production type, but all other scenario reports ignored this production process. Also, during expert consultation, biomass gasification was not perceived a significant contribution and its controversies in political debates recently do not provide solid ground to include this technology in the visions. In the appendix F, **the share of hydrogen in the final energy demand** in the scenario reports are presented. Most scenarios present shares of hydrogen up to 25%. To enable scaling up of technologies, cost reduction and acquire necessary investments for the infrastructure development, it is assumed that larger shares of hydrogen will be required. Furthermore, following the momentum that the development of hydrogen experiences, a higher utilization of hydrogen is assumed than is currently presented in the scenario reports.

Dedicated offshore wind farms directly linked to electrolysers are included in the visions, while there was no role determined for this system element in the scenario reports. Recent strategy announcements indicate that the linkage between offshore wind farms and electrolysers is on the agenda. Shell announced 10 GW dedicated offshore wind in the NortH2 project, Vattenfall & Ørsted tendered for 760 MW dedicated offshore wind but did not win, and BP & Nouryon are forming coalitions as well (2020; Port of Rotterdam, 2020b). These are just announcements and feasibility studies are not yet performed, but it indicates the relevance to include dedicated offshore wind farms in the pathways.

The installed capacities of electrolysers and H_2-to-power installations are set in such way that there are no hours without load (hrs of blackout), but that the installed capacities are minimal. This turns out to be significantly lower than in the II3050 and NvdT scenarios. All visions are constructed in such way that their values remain roughly within the boundaries set by the scenario reports. The scenario reports presented the boundaries of the playing field in which more feasible visions and pathways can be created. This also holds for the energy system costs that are calculated in the ETM.

All visions expect a significant development of offshore wind and electrolyser capacity since this is the most promising technology to be used in the Netherlands. Awaiting the development of scale in other, more economically determining, countries, it is expected that this is the technology of interest to the Netherlands. **Hydrogen as fuel for shipping and aviation sector** is not included. ETM does not offer the possibility for **international transport** (shipping + aviation) to run on hydrogen.

The expected growth of industries towards 2050 is assumed to be similar to corresponding II3050 scenarios. The scenarios all follow the growth of demand sectors such as industry based on the reference scenarios of II3050 that served as starting points for the visions.

Import and export only depends on net annually balance between supply and demand. Whether there is import/export is only determined by the balance between supply and demand, while in reality this has also to do with prices. Also, the storage limit could be expanded to eliminate export, but ETM models it in such way that it is optimized on a cost base.

The losses projected are the distribution losses, since the conversion losses are not of any influence to the flow in the pipelines, which is important for this research. The conversion losses only influence the installed capacities.

In the ETM scenarios of II3050 specific parts of offshore wind are reserved for the production of **aviation and shipping fuels**. These are not included in the total offshore wind capacity mentioned in the description of the visions, but are taken into account regarding the offshore wind potential of the North Sea.

It is assumed that the **maximum offshore wind capacity** for the Netherlands in 2050 will be around 60 GW. This is also the amount required to keep the future annual energy systems costs at a reasonable level (**264**).

In some scenario reports, hydrogen is not used as feedstock, however this is a very applicable option used in many other reports. European Commission and FCH JU draw image that hydrogen could provide up to 25% of final energy demand by 2050 and describes the role for hydrogen as feedstock in industry (JU, 2019). Also the hychain-1 project of ISPT describes a large role for hydrogen as feedstock in industry (ISPT, 2019a). Sometimes, there is no feedstock demand for hydrogen in the starting year of the ETM, because this data is on a municipal level often unknown in the 'Klimaatmonitor'. This is the reason why it is sometimes set to zero by the ETM in the starting year of some scenarios. This presents a major problem for the regionalization of the visions of this research to the industrial Cluster Rotterdam.

Appendix H

Background data end-visions

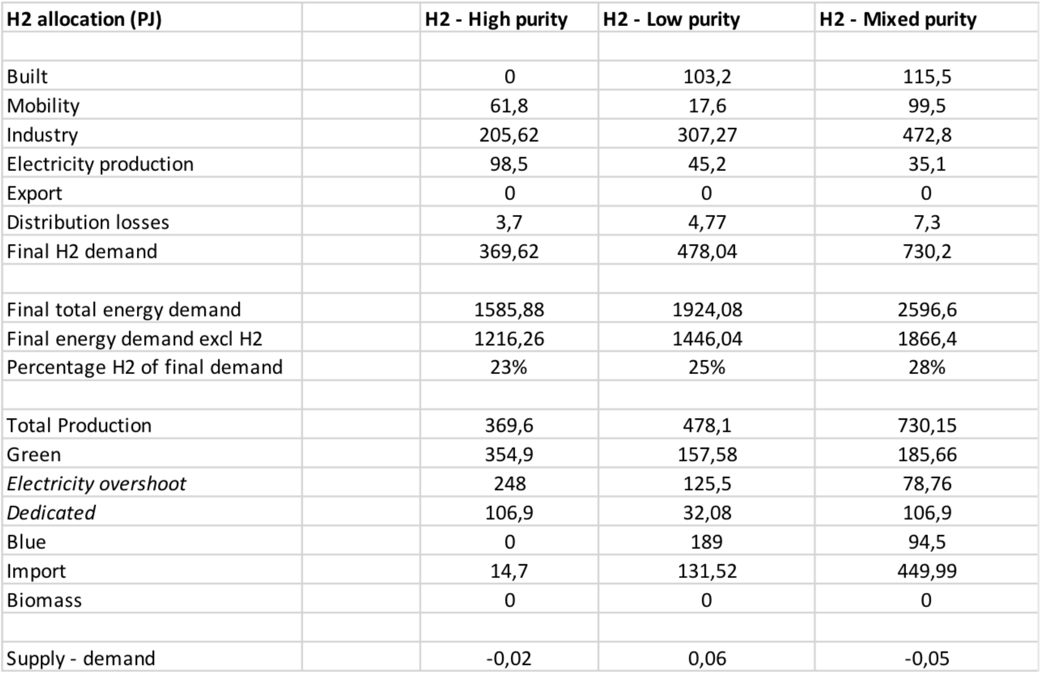
Sector	Independent variables	Dependent variables
General	Nr House holds	Distribution losses (PJ)
	Population	
	& of growth of all industrial sectors	
Hydrogen demand	% Hybrid heat pump hydrogen (houses)	Heat for households (PJ)
	% District heating (buildings)	Heat for district heating (PJ)
	% District heating (houses)	Fuel for transport (PJ)
	% FCEV (passenger)	Heat for industry (PJ)
	% FCEV (public bus)	Feedstock fertilizer production (PJ)
	% FCEV (freight transport)	Feedstock chemical industry (PJ)
	% H_2 - fired heater refineries	Power sector (PJ)
	% H_2 - fired heater fertilizers	Export (PJ)
	% Fertilizer feedstock from H_2 net	
	% H_2 - fired heat chemical industry	
	% H_2 feedstock chemical industry	
	% H_2 as energy carrier in other industry	
	% of growth of all industries	
Hydrogen supply	Installed capacity offshore wind	H_2 from offshore wind (PJ)
	Installed capacity H_2 - to-power	H_2 from electricity overshoot (PJ)
	Installed capacity H_2 heater for distict heating	SMR + CCS (PJ)
	Installed capacity offshore wind for H_2	SMR (PJ)
	Installed capacity SMR	Import (PJ)
	Installed capacity SMR + CCS	
Other	Installed capacity power-to-H_2	GWh storage

Table 24: *Independent and dependent variables in the modelling of the end-visions in the ETM.*

For some of the independent variables, the value of the II3050 reference scenarios are taken. Some variables are adjusted to increase reliability or to enable the significant distinction of the end-visions. If this is the case, assumptions are made and explained. The values are outlined in the table below.

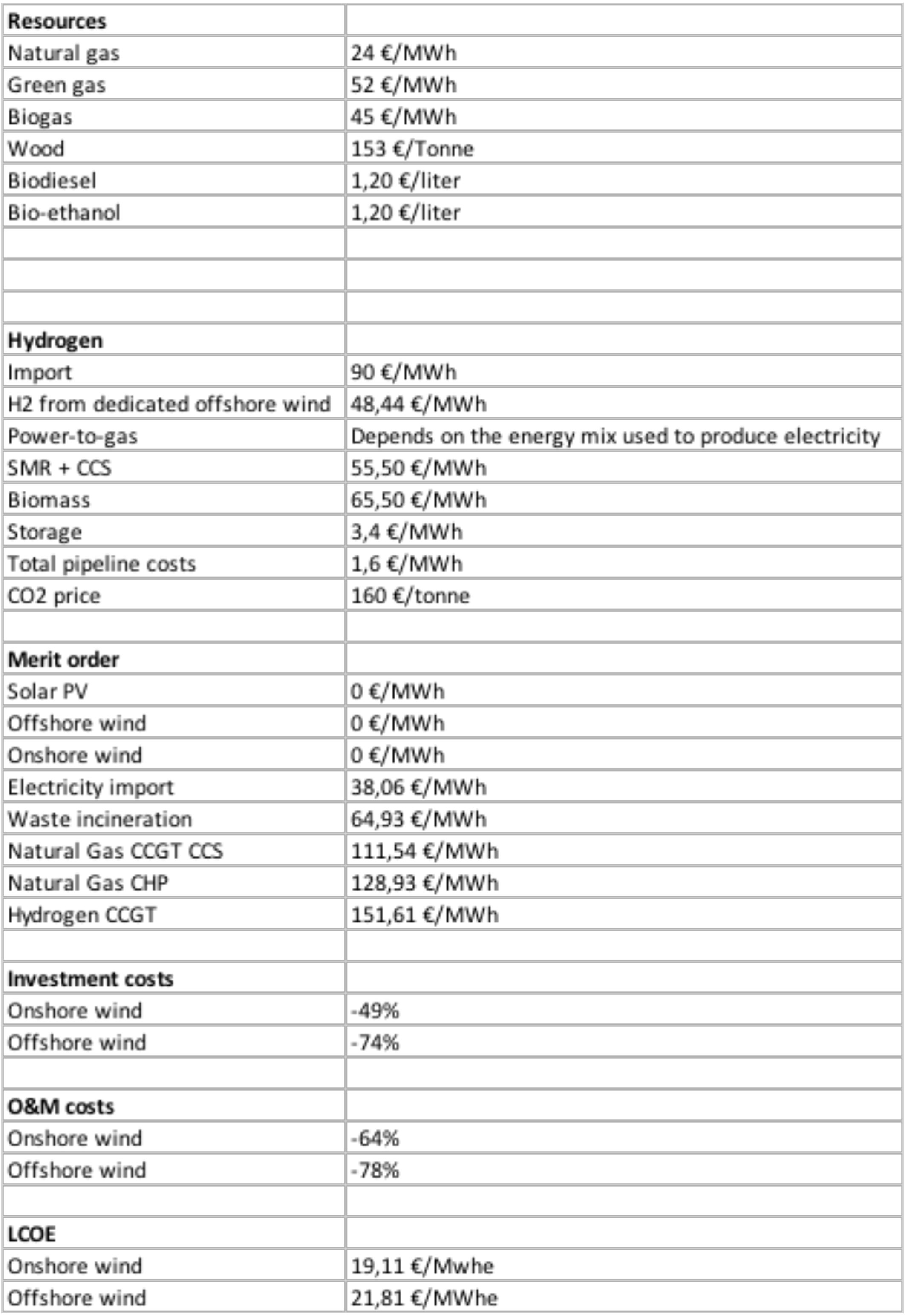
Hydrogen applications in use	**H2 - High purity**	**H2 - Low purity**	**H2 - Mixed**
Built environment			
Hybrid Heatpump	0%	50%	50%
Building attached to district heating	65%	45%	75%
Houses attached to district heating	45%	25%	15%
District Heating H2 (GW)	0	0	0
% H2 in district heating	0%	0	0%
Mobility			
Passenger	25%	5%	20%
Freight	50%	10%	40%
Public busses	50%	10%	40%
Industry			
Refineries			
Growth	14%	36%	50%
Heat	25%	100%	80%
Feedstock	0	0	0
Fertilizers (ammonia)			
Growth	20%	40%	145%
Heat (h2-fired heater)	25%	100%	100%
H2 production central	100%	75%	100%
Local SMR production	0%	25%	
Chemical industry			
Growth	78%	107%	145%
Heat (h2-fired heater)	25%	80%	60%
Feedstock	35%	10%	15%
Other industry			
H2 as energy carrier	20%	50%	30%
Growth	84%	115%	157%
Electricity			
H2-to-Power	32 GW	31 GW	23 GW
Conversion, storage and import			
Electrolysis	25 GW	15 GW	15 GW
Storage	14 TWh	17 TWh	14 TWh
Reforming + CCS	0 GW	10 GW	5 GW
Offshore wind (GW)	31	30	30
Offshore wind for H2 (GW)	10	3	10
Total offshore wind (GW)	41	33	40
Biomass (GW)	0	0	0

Figure 54: *The general description of the end-visions, including development in demand sectors and installed capacities.*



H2 allocation (PJ)		**H2 - High purity**	**H2 - Low purity**	**H2 - Mixed purity**
Built		0	103,2	115,5
Mobility		61,8	17,6	99,5
Industry		205,62	307,27	472,8
Electricity production		98,5	45,2	35,1
Export		0	0	0
Distribution losses		3,7	4,77	7,3
Final H2 demand		369,62	478,04	730,2
Final total energy demand		1585,88	1924,08	2596,6
Final energy demand excl H2		1216,26	1446,04	1866,4
Percentage H2 of final demand		23%	25%	28%
Total Production		369,6	478,1	730,15
Green		354,9	157,58	185,66
Electricity overshoot		248	125,5	78,76
Dedicated		106,9	32,08	106,9
Blue		0	189	94,5
Import		14,7	131,52	449,99
Biomass		0	0	0
Supply - demand		-0,02	0,06	-0,05

Figure 55: *Hydrogen allocation to demand sectors in end-visions.*



Resources	
Natural gas	24 €/MWh
Green gas	52 €/MWh
Biogas	45 €/MWh
Wood	153 €/Tonne
Biodiesel	1,20 €/liter
Bio-ethanol	1,20 €/liter
Hydrogen	
Import	90 €/MWh
H2 from dedicated offshore wind	48,44 €/MWh
Power-to-gas	Depends on the energy mix used to produce electricity
SMR + CCS	55,50 €/MWh
Biomass	65,50 €/MWh
Storage	3,4 €/MWh
Total pipeline costs	1,6 €/MWh
CO2 price	160 €/tonne
Merit order	
Solar PV	0 €/MWh
Offshore wind	0 €/MWh
Onshore wind	0 €/MWh
Electricity import	38,06 €/MWh
Waste incineration	64,93 €/MWh
Natural Gas CCGT CCS	111,54 €/MWh
Natural Gas CHP	128,93 €/MWh
Hydrogen CCGT	151,61 €/MWh
Investment costs	
Onshore wind	-49%
Offshore wind	-74%
O&M costs	
Onshore wind	-64%
Offshore wind	-78%
LCOE	
Onshore wind	19,11 €/Mwhe
Offshore wind	21,81 €/MWhe

Figure 56: *Specification of costs in the energy transition model used for the end-visions..*

Appendix I

Vision 1: H_2 - High purity

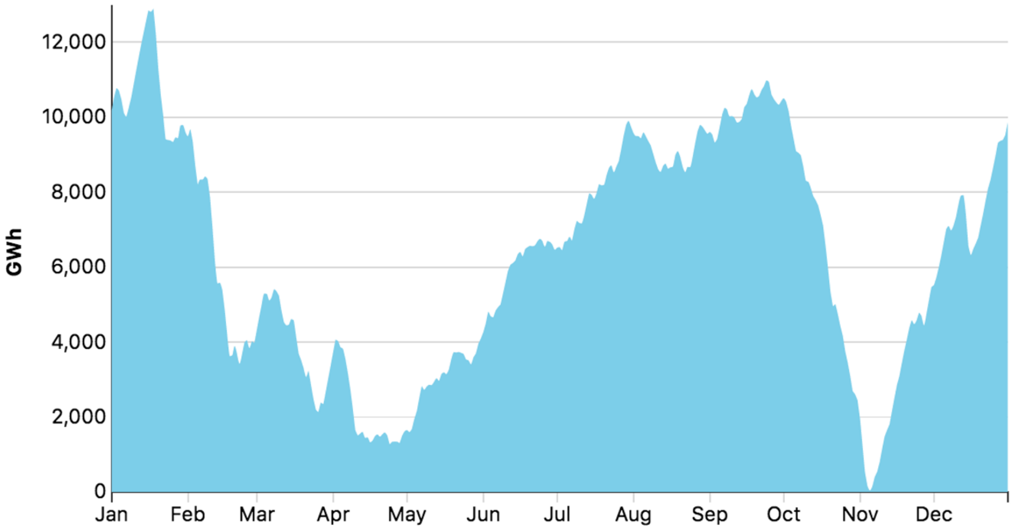


Figure 57: *Vision 1: Annual hydrogen storage for the daily mean for the year 2050.*

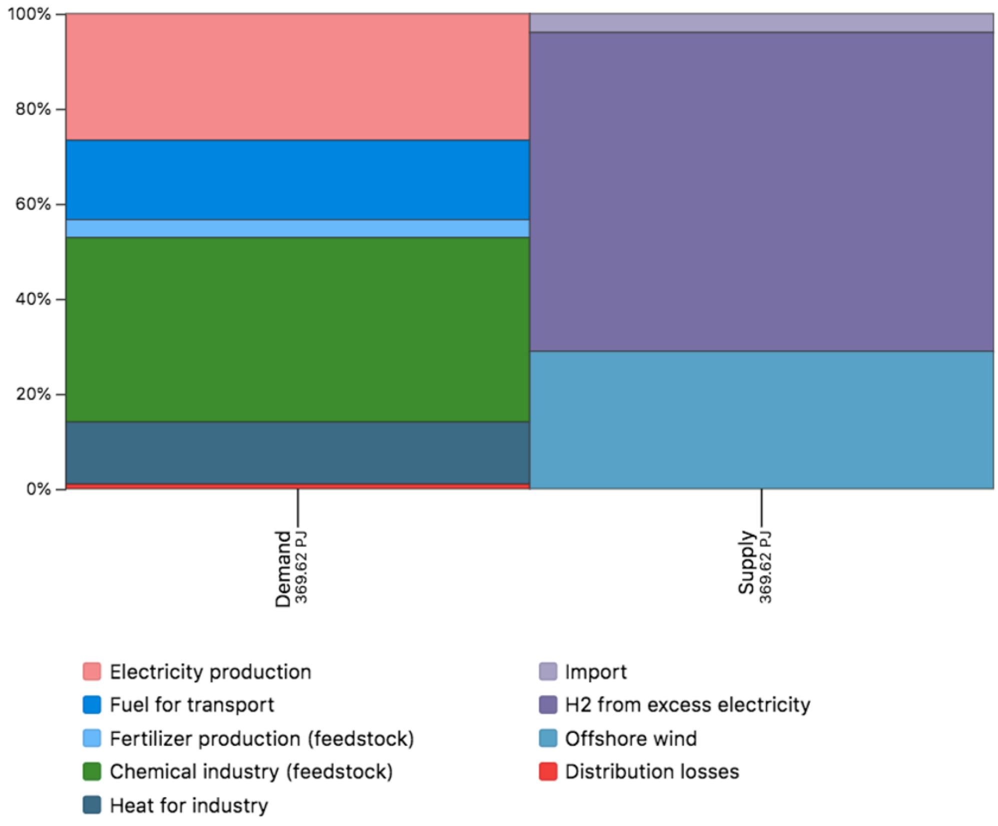


Figure 58: *Vision 1: Annual hydrogen supply and demand volumes for 2050.*

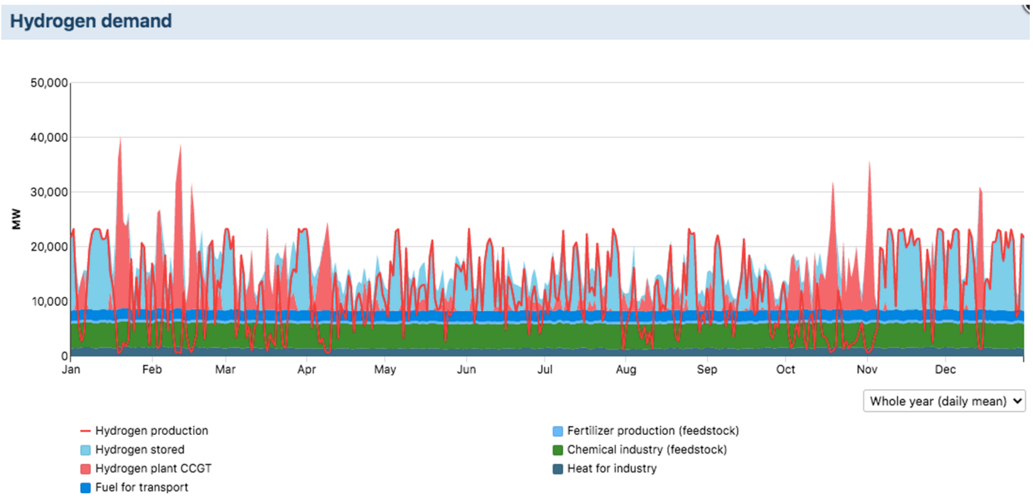


Figure 59: *Vision 1: Yearly hydrogen demand for 2050.*

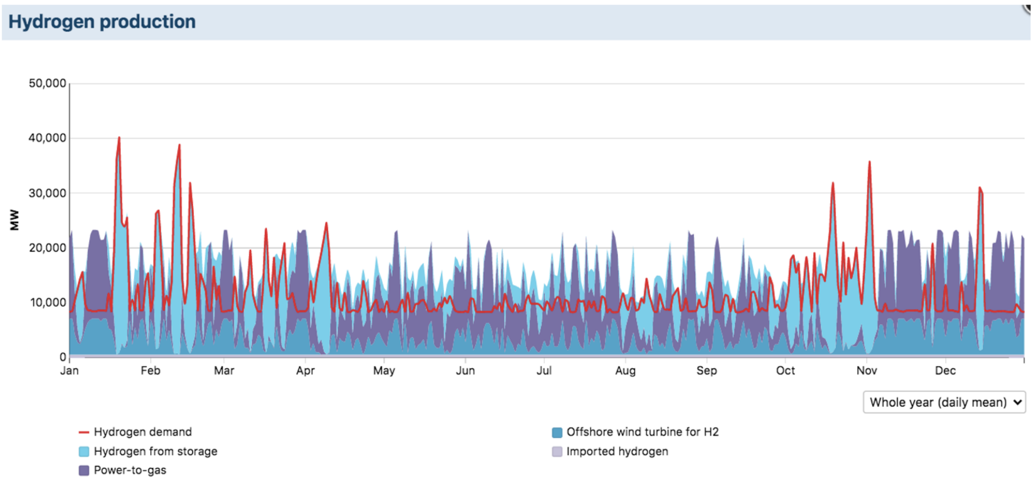


Figure 60: *Vision 1: Yearly hydrogen production for 2050.*

Appendix J

Vision 2: H_2 - Low purity

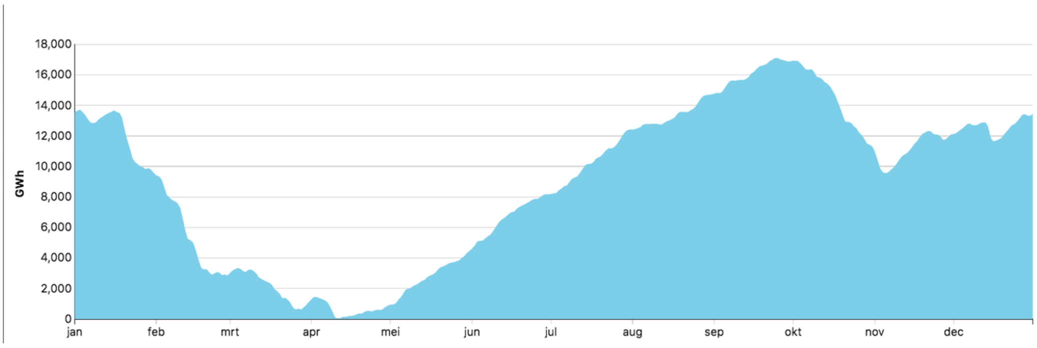


Figure 61: *Vision 2: Annual hydrogen storage for the daily mean for the year 2050.*

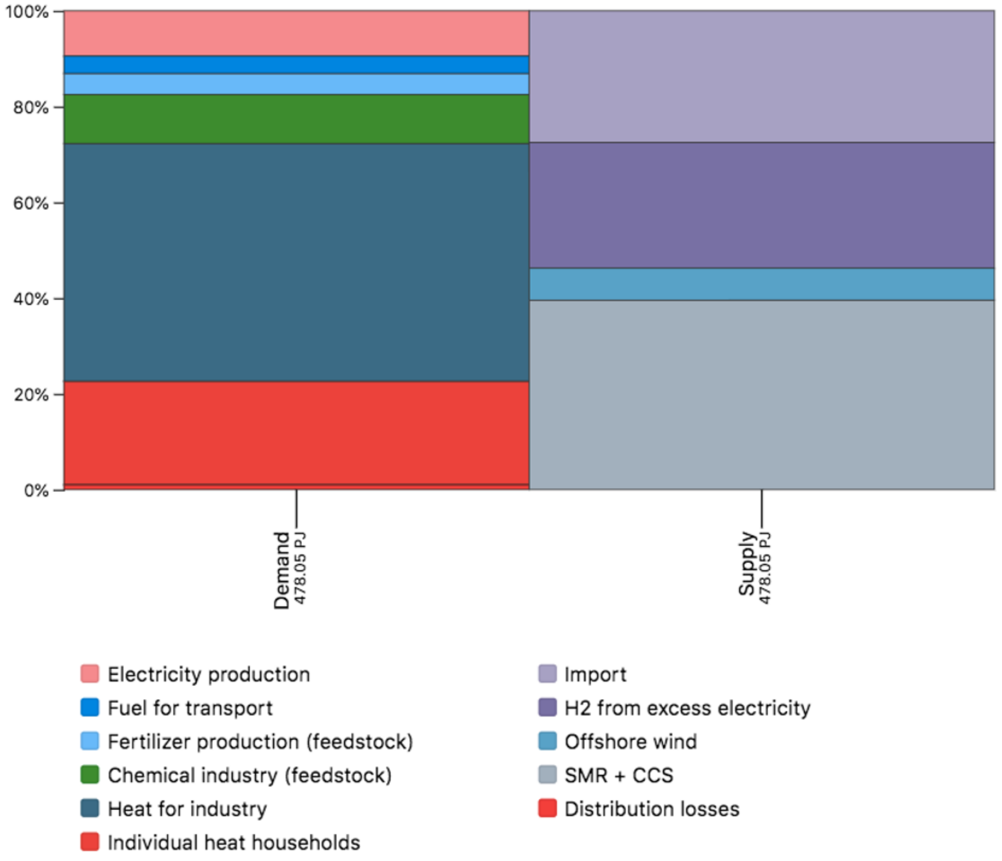


Figure 62: *Vision 2: Annual hydrogen supply and demand volumes for 2050.*

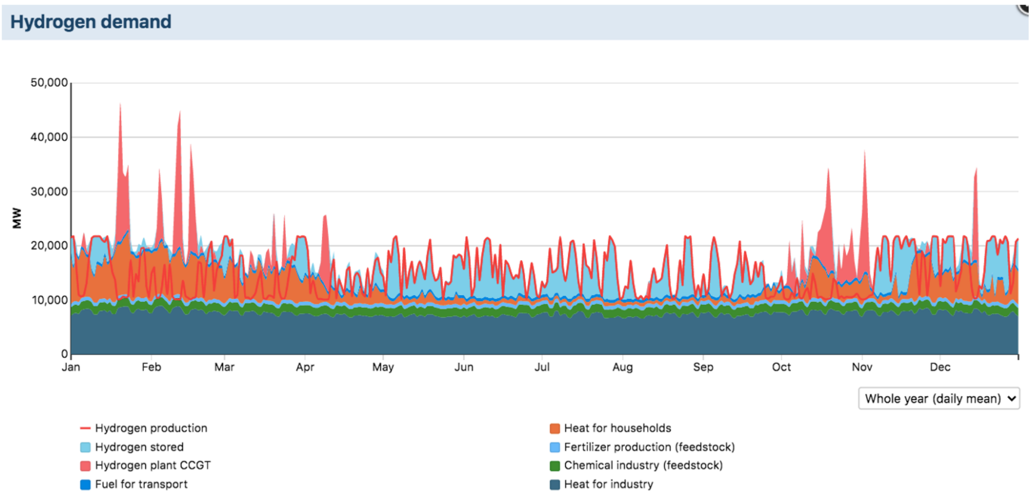


Figure 63: *Vision 2: Yearly hydrogen demand for 2050.*

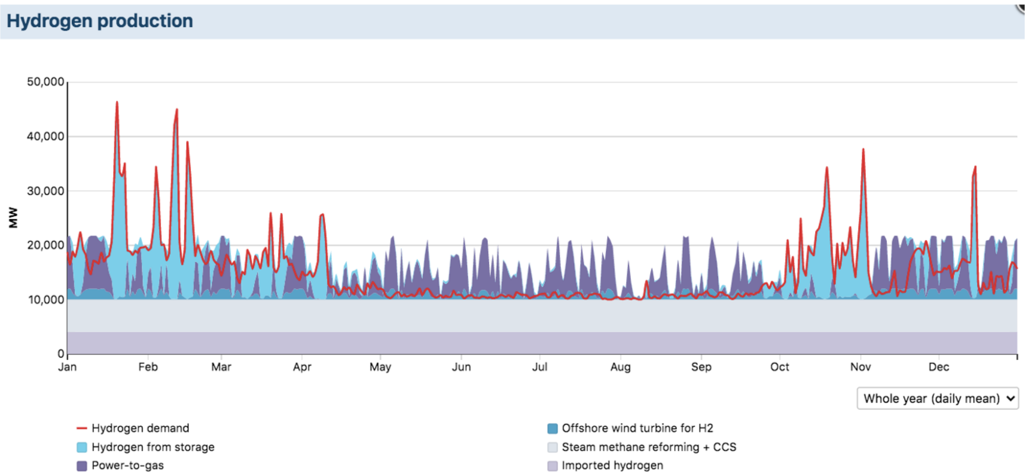


Figure 64: *Vision 2: Yearly hydrogen production for 2050.*

Appendix K

Vision 3: H_2 - Mixed

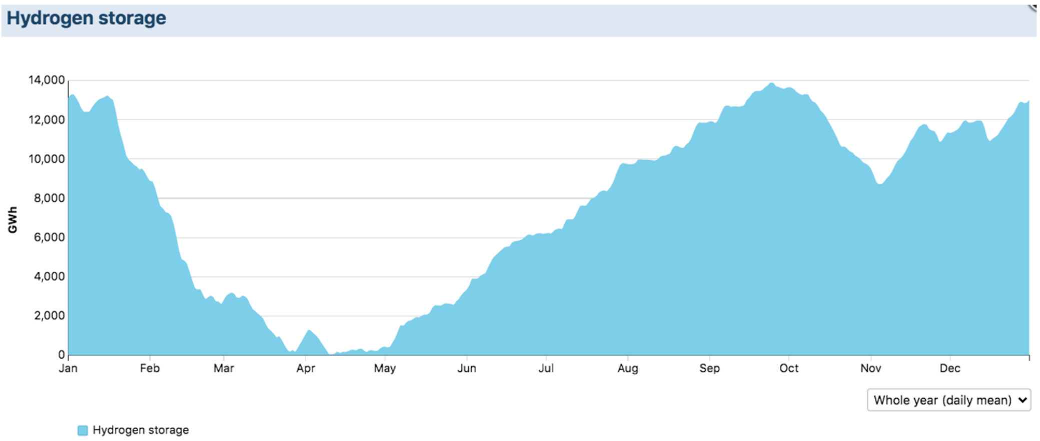


Figure 65: *Vision 3: Annual hydrogen storage for the daily mean for the year 2050.*

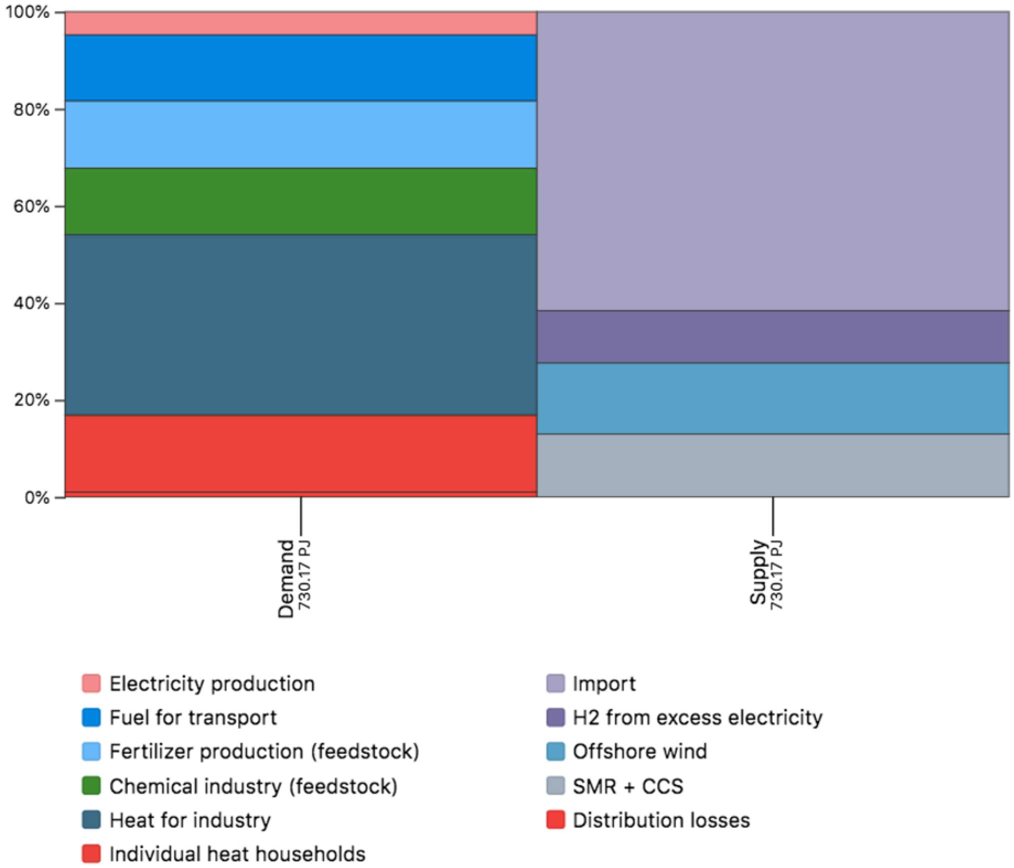


Figure 66: *Vision 3: Annual hydrogen supply and demand volumes for 2050.*

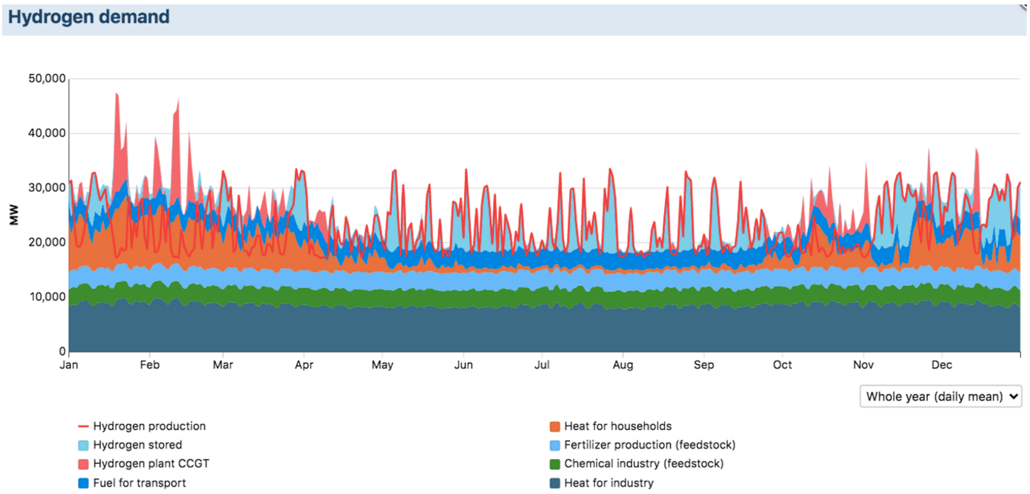


Figure 67: *Vision 3: Yearly hydrogen demand for 2050.*

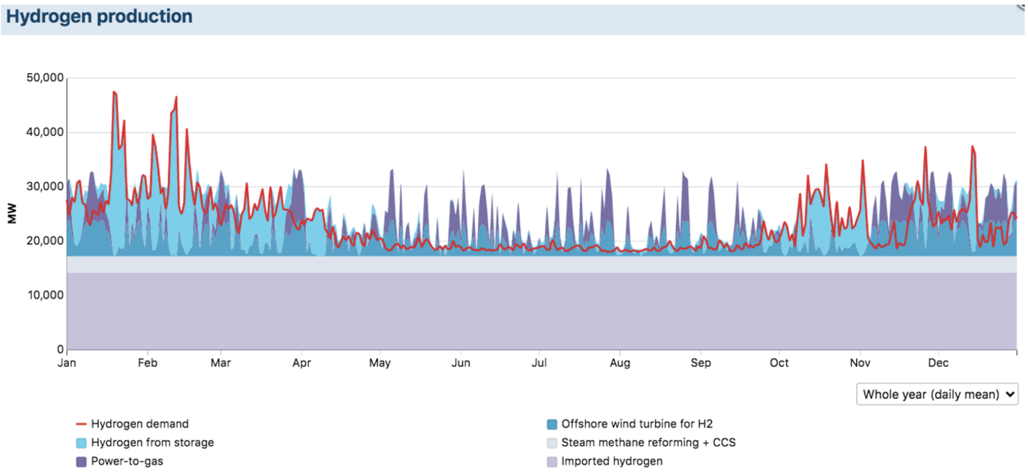


Figure 68: *Vision 3: Yearly hydrogen production for 2050.*

Appendix L

Interviews

Company	*Interviewee*
Eneco	R. Arkesteijn
TU Delft	A. van Wijk
Shell	R. van Grinsven
Gasunie	R. Schutte
Deltalinqs	D. Kuipers
Nouryon	M. de Vries
Air Liquide	J. Oldenziel
Ministry of Economics and Climate Affairs	M. Hamelink
Province of Zuid-Holland	G. Priester
Port of Rotterdam	M. Akkers

Table 25: *List of interviews*

Interview structure: The duration of the interviews differed between 40 minutes and 90 minutes, dependent on the agenda of the interviewee. The following structure was prepared to use as baseline during the interviews. However, the semi-structured approach provides room to deviate and explore interesting arguments and ideas during the interview. The interviews are processed following the theory of Burnard (Burnard, 1991) Interview stages:

1. Introduction
    - Request for cooperation, consent on recording
    - Introduction of myself and topic
    - Introduction of interviewee and company; role in hydrogen system
2. Scenario discussion/verification
    - Feedback
    - Improvements, update on recent developments, changes based on your decisions?
3. Actor analysis
    - Perspective upon relevant value chain elements
    - Perspective upon pipeline alternatives

  - What are the critical requirements for future system?
  - What are currently experienced challenges and bottlenecks in transition period? And in the short- to middle-term? How can these be solved?

4. Pathways
   - What is the influence of the varying production and demand predictions (in scenarios) on the transition strategy?
   - What are key aspects of the pipeline network in this regard?
   - What is the your ideally projected future outlook of the network?
5. Concluding
   - Thanking interviewee; ask for permissions and secrecy
   - Offering to send the interview worked out first and to send the report after

Appendix M

Transition issues

Challenges	Possible actions	Results, consequences	Actors involved	Vision applicable to
U1. *Industrial demand volumes absorb full green H_2 supply flow*	▪ Use blue H_2 for industrial heating market ▪ Use refineries as guaranteed demand sink in period where feedstock and mobility markets are in development phase	▪ Ability to make significant impact with small volumes of green H_2 in markets with no alternatives ▪ More markets mean more certainty for future hydrogen system	Network operators, Built environment, Government, Mobility, Industry	Vision 1
U2. *Complexity of interdependency value chain elements*	▪ High-level cooperation in joint ventures or in coalitions facilitated by government, province or PoR ▪ Subsidies required to make investments attractive ▪ Interconnect to national backbone to provide certainty, seasonal storage	▪ Alignment in volume development of all elements ▪ Avoid curtailment in later phases; effective path towards end-vision ▪ Seasonal storage provides balance and ability to deal with fluctuations	All system actors	All visions
U3. *High capital costs limit role of smaller companies*	▪ Enable network operators to act as aggregator and initiate electrolyser projects in which smaller companies can contribute	▪ Enable smaller companies to profit from economies of scale without carrying full costs ▪ Increased number of competitors in the market; fair competition, possibly decentralised	Network operators, Minor system actors, Government	Vision 1
U4. *Prevent blue H_2 from being an obstacle in the development of green H_2*	▪ Policy mechanisms to enforce, if needed, the phase out of blue H_2 ▪ Use blue H_2 to scale up infrastructure and demand market in such way that green H_2 can take over with minimal adjustments ▪ Avoid blue H_2 from attracting resources that could have been assigned to green H_2 ▪ Long-term strategic planning	▪ Investments in blue H_2 are indirectly also contributing to green H_2 ▪ Blue H_2 is phased out at the right time ▪ Decarbonized end-vision	Government, Electrolysis, Reforming	Vision 2 & 3
U5. *Upscaling by international market*	▪ Fully benefit North Sea potential, but the Netherlands will never be self-sufficient ▪ International market enables to benefit from the wide applicability of H_2, so not necessarily bad	▪ Consequence is that Netherlands is dependent upon regions where H_2 is produced at lower costs, especially 'yellow' H_2 ▪ Net export on a yearly base will never be reached	Area development, Import, Export, Government	Vision 3

Challenges	**Possible actions**	**Results, consequences**	**Actors involved**	**Vision applicable to**
U6. *Increase market volume of electrolysers (from niche to regime)*	▪ Contracted agreements between actors supply and demand side guarantees investment ▪ Increase R&D in electrolysers by utilizing knowledge and liquidity of international market at countries where renewable energy is provided at baseload (hydropower) ▪ Stepwise upscaling of capacities for educational purpose	▪ GW-scale electrolysers ▪ Cost reduction by profit from international scale; competitiveness green H_2 nationally; development of H_2 at regime level for the next transition phase ▪ Sufficient volumes to make pipeline transportation beneficial	Network operator, Industry, Joint ventures, Government	All visions

Table 26: *Interpretation of 'upscaling technology and volumes' issue.*

Challenges	**Possible actions**	**Results, consequences**	**Actors involved**	**Vision applicable to**
S1. *Public vs private network (ownership)*	▪ Dealing with sensitive opinions ▪ Create market competitiveness and provide system actors with a choice what system to use ▪ Early realisation of backbones to attract industrial pipeline operators ▪ Align investment plans and benefit from industrial investments in private pipelines to connect later on to backbone	▪ Result can either be two separated networks operated at the same time or the integration of the private existing network in the public infrastructure ▪ Two separately operated systems in the first phase ▪ Connection of backbone with centralised industrial production of hydrogen enables supply to other demand sectors	Network operators, Industry	All visions
S2. *Complexity multi-purpose character hydrogen; set purity standard*	▪ Investigate economic and strategic consequences of both a high-purity and low-purity norm, i.e. required PSA units, conversion units etc. ▪ Align type of production (green/blue) with type of demand (heat or feedstock/fuel) ▪ Determine purity standards over the years; green H_2 is preferred end-situation, but determine what is most-effective in short- to middle-term	▪ The optimal purity depends on volumes, costs of purification and will change over time during the transition period ▪ Too many uncertainties and unclarities in the strategy of network operator causes project developers to start own infrastructure ▪ Varying with system standards requires adjustment to end-use appliances or additional purification steps	Network operators	All visions

Challenges	Possible actions	Results, consequences	Actors involved	Vision applicable to
S3. *Open accessible integrated system*	▪ Enforce a connection obligation ▪ Cooperate with industrial sector that is initiating construction of private pipelines ▪ Create open market with free entrance, low thresholds and liquidity	▪ The level of open accessibility, as with electricity network is not feasible on short-term ▪ Socialized hydrogen system where all actors have possibility to enter market ▪ Industry benefits from avoiding construction and costs by using public infrastructure	Network operators, Government	Vision 1 & 2
S4. *Combining the two different H_2 cycles in one network: chemical product and heat source*	▪ Agree whether hydrogen is a replacement for natural gas, a chemical product or serves as both ▪ Determine feasibility of utilization high-purity H_2 also for heating in long-term ▪ Bridge contradicting perspectives existing and future regime actors ▪ Observe that natural gas is a common resource, where hydrogen is a chemical product ▪ Investigate the differences with the transition to natural gas in the 60s, where market was not liberalized	▪ Definition of the role of H_2 will provide a base for the design of and required standards for the pipeline infrastructure ▪ Clear rules and norms regarding ownership and responsibilities in the H_2 network ▪ Acknowledgement of the complexity that the currently liberalized market causes, enables constructive assessment of the role of the network operator	All system actors	All visions, but mainly 3
S5. *Separated ownership network layers increases complexity transition*	▪ Natural gas/electricity network taken as reference for desired public network, but take perspective of water network, heat network or chemical product networks which are differently organized ▪ Enable network operator to initiate production and demand development projects in the transition period ▪ High-level cooperation	▪ Possible result could be that the network operator is in the transition phase also owner of the molecular flow in the future system ▪ An active investment role of the network operator in other activities could cause inequal support for market parties ▪ Coalitions and joint ventures in early phase of transition can bundle forces to speed up transition.	Government, Network operators	All visions

Challenges	Possible actions	Results, consequences	Actors involved	Vision applicable to
S6. *Range of Wobbe-index increases complexity*	▪ Narrow consistent range is required to standardize end-use appliances ▪ Operation of pipeline network and control of gas composition monitored by one actor ▪ Incl. H2 in gas directive	▪ Infeasibility for blending H_2 in NG, especially with increasing share of H_2 over the years ▪ Clear set of norms and standards for molecules in the network	Network operators	All visions
S7. *Maintain desired purity of H_2 throughout the chain*	▪ Possible combined ownership of molecules and pipelines makes it easier to monitor ▪ Operate one purity of H_2 throughout the full chain ▪ Investigate operation of two networks, i.e. as with high-caloric and low-caloric for NG	▪ Supply of the guaranteed energetic value in the gas composition ▪ Increases infeasibility of physical blending	Network operator	Vision 1 & 3

Table 27: *Interpretation of 'systems standards and organization' issue.*

Challenges	Possible actions	Results, consequences	Actors involved	Vision applicable to
P1. *Incentivize unprofitable upscaling volumes*	▪ Implement virtual blending obligation ▪ Develop plans to increase physical blending limits, but this is perceived by many as infeasible ▪ Introduce separate upscaling instrument next to SDE++ ▪ Take away uncertainty around ETS-price to enable reliable business case ▪ No green H_2 without subsidies ▪ Do not apply tax on green H_2 up until certain level; still billing of excessive consumption and incentivize reduction	▪ Generation of revenues for public investment ▪ Physical blending not expected ▪ Effective policy instruments ▪ H_2 expected to compete with natural gas and outcompete district heating in middle-term ▪ Investment decisions made on a short notice; regulation is ready to comply with projects	Ministry	All visions; mainly vision 1

Challenges	**Possible actions**	**Results, consequences**	**Actors involved**	**Vision applicable to**
P2. *Long-term consistency policies*	▪ Create long-term political strategies in agreement with system actors and make sure that all actors keep to what has been agreed ▪ Take away uncertainty regarding ETS ▪ Develop policy roadmap towards 2050 with clear view of hydrogen network instead of natural gas as end-situation	▪ If no consistency, companies in energy sector will start projects in other countries with stable policies ▪ The future system will comply with policy goals set at the begin phase	Ministry, Province, PoR	All visions
P3. *Comply directives, mechanisms and legislation*	▪ Adjust SDE++ to relevance for blue H_2 ▪ Increase interest for CCS in politics ▪ Combine electricity and gas directive in a general energy directive including hydrogen	▪ Blue H_2 becomes attractive to stimulate transition towards green H_2 ▪ General energy directive stimulates system integration	Ministry, Province	All visions, mainly vision 2
P4. *Facilitate phase-out blue H2 after transition*	▪ Clarify long-term plan for CO2-tax ▪ Increase competitiveness green H_2 ▪ Make EB and ODE CO2-dependent to increase costs of blue H_2 ▪ Stop subsidies for CCS at specific point ▪ Tax to increase natural gas prices	▪ Blue H_2 is phased out at moment in future where it is not contributing anymore to development of green H_2	Ministry	All visions, but mainly vision 2
P5. *Complexity transition roles public actors*	▪ Open-up discussion between all system actors about expectations for role of government ▪ Direct the role of public actors as initiators and facilitators safeguarding the systems perspective ▪ Stimulate private infrastructure in starting phase that could collide to collective infrastructure when demand sectors are ready	▪ Pro-active role of government can stimulate built environment to be included in plans ▪ Changing role of public network operator between transition phase and end-situation ▪ Clear role division between national network operator and regional network operators	All public actors	All visions

Challenges	**Possible actions**	**Results, consequences**	**Actors involved**	**Vision applicable to**
P6. *(In)Ability of market to fulfil hydrogen transition by itself*	▪ Design directives and laws in general sense and leave details open to be filled in by trial and error in the process; too much interventions limits design space ▪ Support investments by partially capture unprofitable peak by subsidies to guarantee volumes ▪ Stimulate market to obtain mutual agreement on responsibilities in transition phase and end-situation by itself	▪ Subsidies support corporates to make investments, also if market volumes are insufficient for business case ▪ Clear task division in future market; if not, regulation required ▪ Avoid full transition costs to be carried by government	All system actors	All visions

Table 28: *Interpretation of 'policy and institutions' issue.*

Challenges	**Possible actions**	**Results, consequences**	**Actors involved**	**Vision applicable to**
E1. *Cost price reduction; economic competitiveness*	▪ Benefit from volume and efficiency development at international market ▪ Currently, purification further than 95% is not economically efficient; ensure that it is ▪ Develop business cases with baseload green electricity supply to gradually increase electrolyser capacity and learn by example, if needed in other countries	▪ Importing 'yellow' hydrogen at low costs ▪ Extensive interconnections with international market; PoR as hydrogen hub ▪ Economic competitiveness of green H_2 will incentivize companies to adjust production processes to utilize more H2H_2 ▪ Industrial sector could be largely decarbonized; no role for natural gas	Government, Network operators, Industry, PoR	Vision 3
E2. *Certainty for investment*	▪ Create clarity on factors influencing future price settings ▪ Ensure a market with multiple suppliers and consumers ▪ Utilize public enterprises that can develop volumes without guaranteed demand ▪ Facilitate contracts between different actors on supply and demand side	▪ Investment decisions are made in short-term ▪ Infrastructural development that boosts volume increase of production and demand	All market actors	All visions

Challenges	Possible actions	Results, consequences	Actors involved	Vision applicable to
E3. *Generate public investment*	▪ Trading markets for certificates ▪ Create an open market with multiple suppliers and consumers and liquidity ▪ Compensate the low marginal costs of renewables that will decrease willingness to invest	▪ Throughout the full transition period, there is experienced sufficient investment power to keep moving forward to the next transition phase	Government	All visions, but mainly vision 1
E4. *Realization of market liquidity*	▪ Create an open market with multiple suppliers and consumers ▪ Utilize all market sectors in the long term; built environment has few alternatives and no possibility to move ▪ Incentivize by subsidy instruments	▪ Widespread market development with international character ▪ On long-term, subsidies and governmental support not needed	Government	All visions
E5. *Ensure economic position of PoR and Netherlands*	▪ Invest in conversion terminals and pipeline connections to Germany (+ Belgium) in near-term ▪ Incentivize industry to stay and decarbonize, although the source of energy is not closely located anymore, as it was the case with natural gas	▪ Hydrogen demand in PoR and Netherlands significantly increases over the long-term ▪ PoR is the hydrogen hub of North-West Europe	Province, PoR, Government, Industry	All visions, but mainly vision 3
E7. *Profitability of pipeline network*	▪ Enable required volumes to fill pipeline capacities ▪ No blending ▪ Socialize infrastructure costs where applicable; depends on sector ▪ Financial support for network operators to enable construction of overcapacity	▪ Cost-efficient pipeline infrastructure facilitates development of value chain ▪ Socialization of costs for infrastructure in built environment, in industrial sector on short-term market actors carry costs ▪ Capacity of pipeline network will be at least sufficient for the long-term (2050)	Network operator, Government	All visions, but mainly vision 3

Table 29: *Interpretation of 'economics' issue.*

Challenges	**Possible actions**	**Results, consequences**	**Actors involved**	**Vision applicable to**
I1. *Align hydrogen transition with overall energy transition*	▪ Realize overall goal of decarbonization ▪ Green H_2 replaces gasoline/oil/diesel and feedstocks ▪ Blue H_2 replaces natural gas ▪ Align strategies with long-term expectation for demands in other systems ▪ Align H_2 pipeline development with natural gas transition from low-caloric network to high-caloric network because of stop Groningen field	▪ Optimization of energy transition in general ▪ Minimization of energy transition costs ▪ Maximization of reuse existing assets.	All system actors	All visions
I2. *Functioning of hydrogen as decarbonized flexibility in electricity system*	▪ Upscaling to provide balancing volumes currently provided with natural gas ▪ Construct PtG and pipeline capacities to facilitate very large volume flows required for flexibility ▪ Invest in pipelines to enable long-distance transport by molecules for the electricity system	▪ Security of supply in electricity network ▪ Complementary utilization of hydrogen and electricity (molecules and electrons) in energy system ▪ Even ‘all electric’ scenarios exhibit a major role for hydrogen pipeline transportation	Electrolysis, Storage, Network operator	Vision 1
I3. *Upscaling PtG without using fossil resources for electricity mix*	▪ Ensure stable supply for PtG to enable business case without fossil fuels ▪ Align PtG capacity with renewable capacity	▪ Minimization of curtailment of production units ▪ Gradual investment in capacity	Offshore wind, Government, Electrolysis	Mainly vision 1
I4. *Deploy alternatives (electrification or other decarbonized gasses) where possible*	▪ Electrify direct heat appliances ▪ In PoR strong utilization of residual heat and geothermal energy in industry, built environment and horticulture ▪ Deploy electrons and molecules in complementary way	▪ Reduction of energy use, electrification and supplementation with hydrogen; in this sequence ▪ Optimize energy efficiency throughout entire energy system	All demand sectors, Government	All visions, but mainly vision 1

Challenges	Possible actions	Results, consequences	Actors involved	Vision applicable to
I5. *Align pipeline construction in general energy transition and chemical product flows*	▪ Investigate possibility to build hydrogen pipelines that are allocated in short-term (during period of insufficient H2 volumes) for other chemical products ▪ Combine hydrogen pipeline planning with stopped deployment of low-caloric natural gas ▪ Benefit from mature product flow by pipelines to Ruhr-area ▪ Align residual flows of H_2 with steam production and flows of nitrogen, oxygen and carbon monoxide; waste-to-chemicals	▪ Long-term consistent planning for pipeline construction ▪ Optimize reuse of existing infrastructure ▪ Bundles of pipelines, with possible interoperability ▪ Optimization of waste flows	Network operator, Industry	All visions
I6. *Increase efficiency of energy system as a whole*	▪ Combine electricity, heat and hydrogen transitions to phase out fossil energy	▪ Decarbonized energy system in 2050	Government	All visions

Table 30: *Interpretation of 'integration in the energy system' issue.*

Appendix N

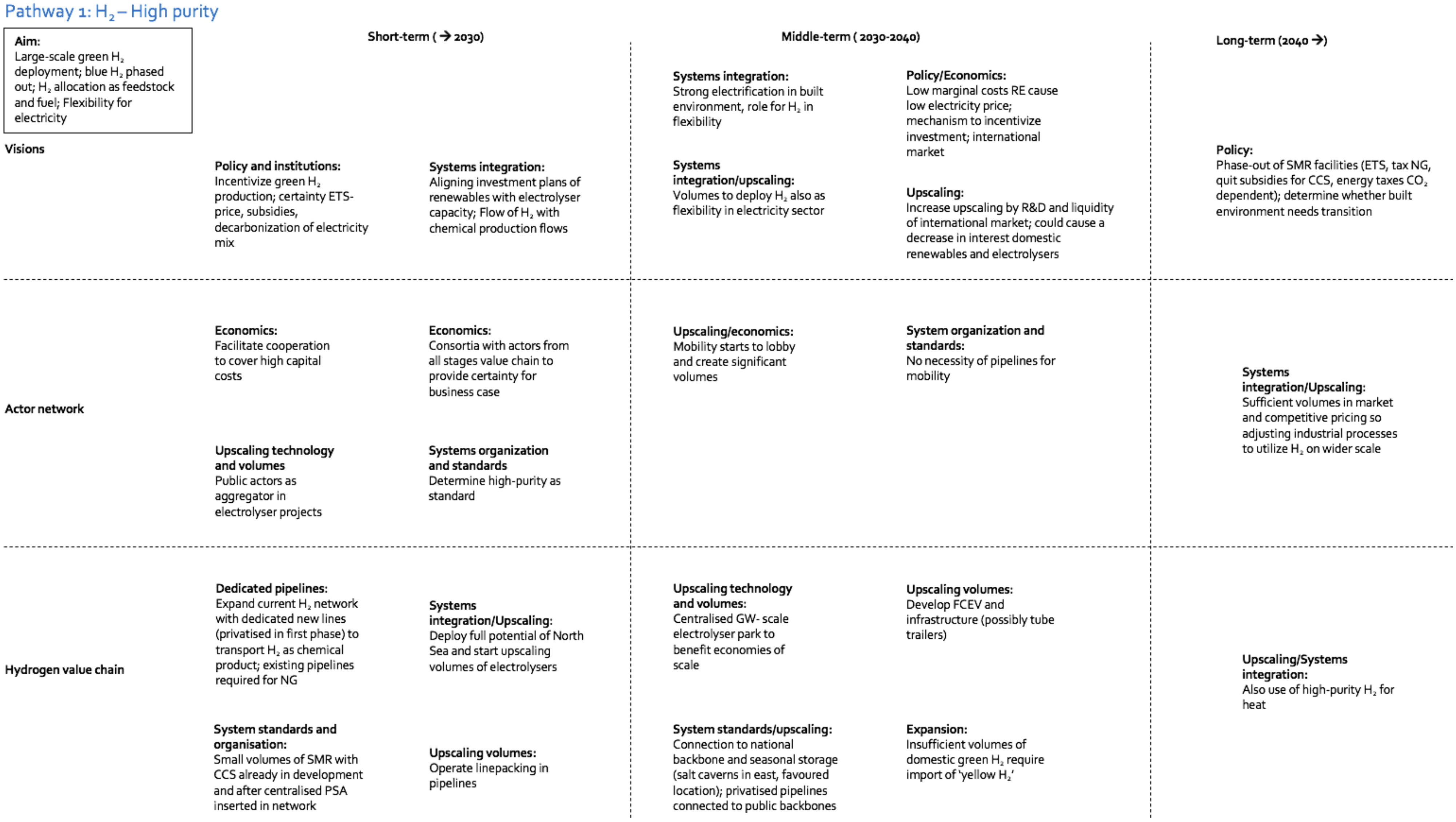
Transition pathways

General actions all pathways

Aim:
Developing a decarbonized energy system with a perceived dominant role for H_2 next to electrification

	Short-term (→ 2030)	Middle-term (2030-2040)	Long-term (2040 →)
Visions	**Policy and institutions:** Consistent energy transition policy (towards 2050) **Policy and institutions:** Adjust gas directive to enable implementation of hydrogen technologies **Systems organization and standards:** Government intervention vs expansion privatised network with regulatory control **Economics:** Implement virtual blending and other mechanisms to generate public investment capacity	**Upscaling technology and volumes:** Cost-price reduction via international market Increase lobby for PoR as hydrogen hub **Systems organization and standards:** Open full-scale developed market with connection obligation, low threshold and liquidity	**Integration in energy system:** Full integration of hydrogen value chain in energy system as major support to electrification
Actor network	**Systems organization and standards:** Bridge contradicting perspectives of existing system actors vs entering system actors **All system actors:** Develop scale in production/infra/demand by cooperation between industry and network operator **Systems organization and standards:** Decide upon system standard	**Policy and institutions:** (Pro-)active of role of government to develop other markets **Economics:** Start coalitions in other markets to invest in transition	
Hydrogen value chain	**Systems organization and standards:** For crucial locations: start adjusting pipelines if reuse is possible. If not, plan construction of dedicated lines – Eliminate blending as alternative **Upscaling technology and volumes:** Generate capacity in the infrastructure to enable upscaling of volumes in industry and provide security of supply (domestic production and demand) **Upscaling technology and volumes:** Built overcapacity to comply with expected future demands	**Upscaling technology and volumes:** Enable other markets to benefit from developed scale by expanding capacities and reachability of pipelines **Economics:** Provide the necessary interconnections to other countries and make PoR ready for import	**Systems organisation and standards:** Open accessible network with high interconnectivity and international character

Figure 69: *Transition pathway visualising general actions required in any situation.*

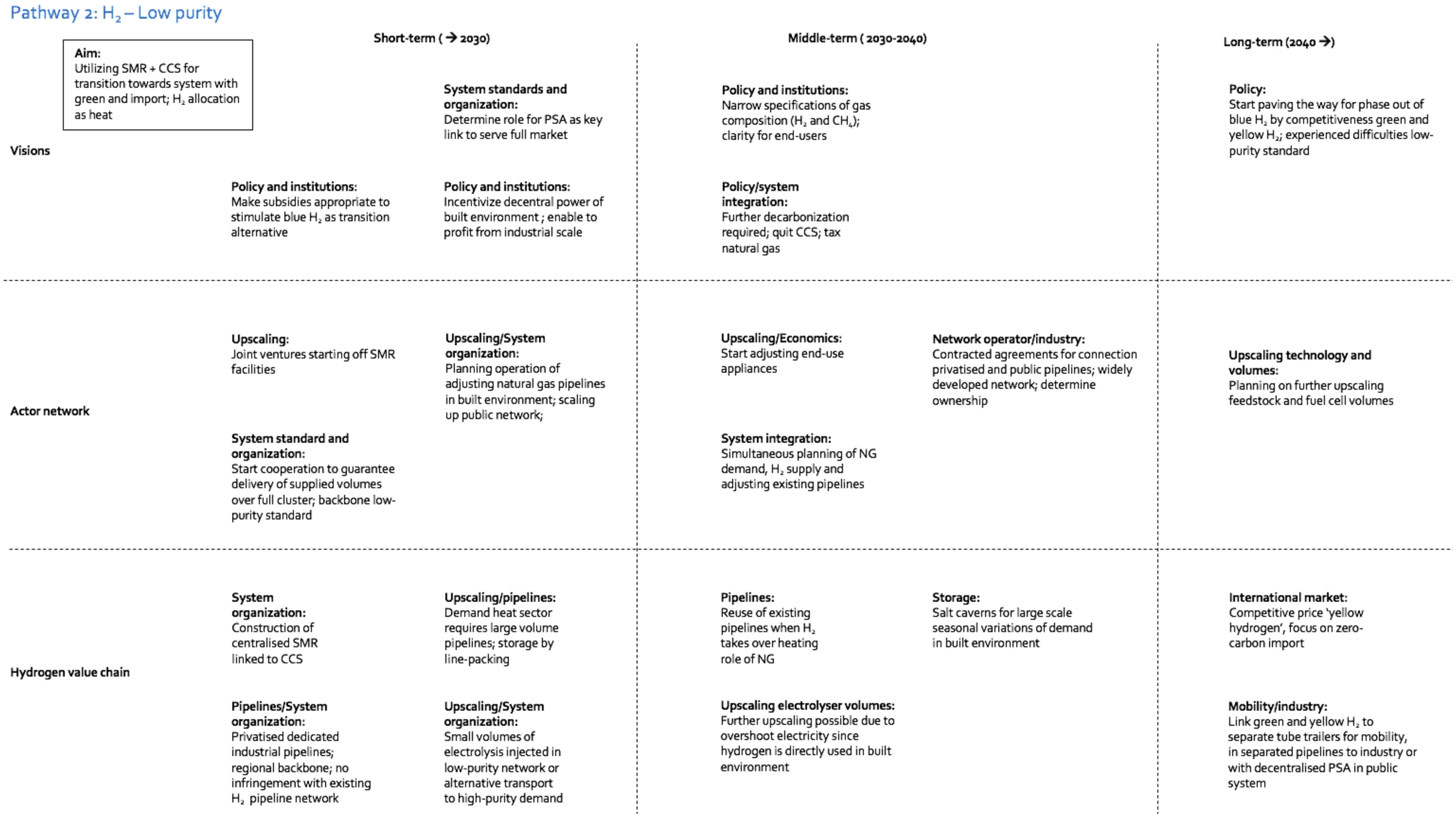


Pathway 1: H_2 – High purity

Aim:
Large-scale green H_2 deployment; blue H_2 phased out; H_2 allocation as feedstock and fuel; Flexibility for electricity

	Short-term (→ 2030)		Middle-term (2030-2040)		Long-term (2040 →)
Visions	**Policy and institutions:** Incentivize green H_2 production; certainty ETS-price, subsidies, decarbonization of electricity mix	**Systems integration:** Aligning investment plans of renewables with electrolyser capacity; Flow of H_2 with chemical production flows	**Systems integration:** Strong electrification in built environment, role for H_2 in flexibility **Systems integration/upscaling:** Volumes to deploy H_2 also as flexibility in electricity sector	**Policy/Economics:** Low marginal costs RE cause low electricity price; mechanism to incentivize investment; international market **Upscaling:** Increase upscaling by R&D and liquidity of international market; could cause a decrease in interest domestic renewables and electrolysers	**Policy:** Phase-out of SMR facilities (ETS, tax NG, quit subsidies for CCS, energy taxes CO_2 dependent); determine whether built environment needs transition
Actor network	**Economics:** Facilitate cooperation to cover high capital costs **Upscaling technology and volumes** Public actors as aggregator in electrolyser projects	**Economics:** Consortia with actors from all stages value chain to provide certainty for business case **Systems organization and standards** Determine high-purity as standard	**Upscaling/economics:** Mobility starts to lobby and create significant volumes	**System organization and standards:** No necessity of pipelines for mobility	**Systems integration/Upscaling:** Sufficient volumes in market and competitive pricing so adjusting industrial processes to utilize H_2 on wider scale
Hydrogen value chain	**Dedicated pipelines:** Expand current H_2 network with dedicated new lines (privatised in first phase) to transport H_2 as chemical product; existing pipelines required for NG **System standards and organisation:** Small volumes of SMR with CCS already in development and after centralised PSA inserted in network	**Systems integration/Upscaling:** Deploy full potential of North Sea and start upscaling volumes of electrolysers **Upscaling volumes:** Operate linepacking in pipelines	**Upscaling technology and volumes:** Centralised GW- scale electrolyser park to benefit economies of scale **System standards/upscaling:** Connection to national backbone and seasonal storage (salt caverns in east, favoured location); privatised pipelines connected to public backbones	**Upscaling volumes:** Develop FCEV and infrastructure (possibly tube trailers) **Expansion:** Insufficient volumes of domestic green H_2 require import of 'yellow H_2'	**Upscaling/Systems integration:** Also use of high-purity H_2 for heat

Figure 70: *Transition pathway visualising general actions required for end-vision 1.*



Pathway 2: H_2 – Low purity

Aim:
Utilizing SMR + CCS for transition towards system with green and import; H_2 allocation as heat

	Short-term (→ 2030)		Middle-term (2030-2040)		Long-term (2040 →)
Visions	**Policy and institutions:** Make subsidies appropriate to stimulate blue H_2 as transition alternative	**System standards and organization:** Determine role for PSA as key link to serve full market **Policy and institutions:** Incentivize decentral power of built environment ; enable to profit from industrial scale	**Policy and institutions:** Narrow specifications of gas composition (H_2 and CH_4); clarity for end-users **Policy/system integration:** Further decarbonization required; quit CCS; tax natural gas		**Policy:** Start paving the way for phase out of blue H_2 by competitiveness green and yellow H_2; experienced difficulties low-purity standard
Actor network	**Upscaling:** Joint ventures starting off SMR facilities **System standard and organization:** Start cooperation to guarantee delivery of supplied volumes over full cluster; backbone low-purity standard	**Upscaling/System organization:** Planning operation of adjusting natural gas pipelines in built environment; scaling up public network;	**Upscaling/Economics:** Start adjusting end-use appliances **System integration:** Simultaneous planning of NG demand, H_2 supply and adjusting existing pipelines	**Network operator/industry:** Contracted agreements for connection privatised and public pipelines; widely developed network; determine ownership	**Upscaling technology and volumes:** Planning on further upscaling feedstock and fuel cell volumes
Hydrogen value chain	**System organization:** Construction of centralised SMR linked to CCS **Pipelines/System organization:** Privatised dedicated industrial pipelines; regional backbone; no infringement with existing H_2 pipeline network	**Upscaling/pipelines:** Demand heat sector requires large volume pipelines; storage by line-packing **Upscaling/System organization:** Small volumes of electrolysis injected in low-purity network or alternative transport to high-purity demand	**Pipelines:** Reuse of existing pipelines when H_2 takes over heating role of NG **Upscaling electrolyser volumes:** Further upscaling possible due to overshoot electricity since hydrogen is directly used in built environment	**Storage:** Salt caverns for large scale seasonal variations of demand in built environment	**International market:** Competitive price 'yellow hydrogen', focus on zero-carbon import **Mobility/industry:** Link green and yellow H_2 to separate tube trailers for mobility, in separated pipelines to industry or with decentralised PSA in public system

Figure 71: *Transition pathway visualising general actions required for end-vision 2.*

Pathway 3: H_2 – Mixed

Aim:
High utilization of all H_2 applications; Blue H_2 in early transition; Green H_2 upscaling later on; less integration in electricity sector

	Short-term (→ 2030)	Middle-term (2030-2040)	Long-term (2040 →)
Visions	**Policy/system standards:** Plan transformation of standard from low-purity to high-purity in middle-term **Policy/system integration:** Incentivize upscaling electrolysers, offshore wind and SMR to develop scale in infrastructure and market; subsidies for electrolysis, SMR and CCS; alignment with policies of electricity system **Policy/economics:** Active internationalization of infrastructure as early as possible; keep up with pace of increasing demand; incentivize industry to stay in PoR	**Policy and institutions:** Quit subsidies blue H_2; cost reduction green H_2; tax natural gas; phase-out blue H_2 **Economics:** Facilitate and investment for PoR to become hydrogen hub; conversion terminals; liquified storage; ammonia; LOHC **Policy/system standards:** Renew legislation and policies for next phase of transition period, where import and green H_2 take over	**System integration:** Very strong developed role of H_2 in all sectors next to electrification; direct use of H_2 in end-use; battery storage
Actor network	**Upscaling/system standards:** Immediate upscaling of public network; consortia with industrial companies to scale up; mutual private/public investment in network; Low-purity standard; Industrial heat is first application	**Electrolysis:** Early utilization of international scale, cost-price reduction and liquidity stimulates upscaling and to keep up pace with international innovations **System standards:** Implement planned transition of low-purity to high-purity **Upscaling/built environment:** 2nd largest market in volumes included early in process; adjustment of end-use appliances; benefit from upscaling by industry	**Industry:** Feedstock industry and adjusting industrial process for utilization of high-purity H_2 **Mobility:** Cooperation with electrolyser owners to receive allocation necessary volumes for FCEV; not necessarily via public pipelines
Hydrogen value chain	**Pipelines/upscaling:** Dedicated public pipelines in industry with regional and national backbone to connect to seasonal storage; use existing hydrogen network if possible **Upscaling:** Seasonal salt cavern storage required in early phase of transition due to quick upscaling and apply seasonal variations in built environment **Pipelines:** Reuse existing pipelines in built environment to speed up transition and expand network **SMR + CCS:** Supports electrolysers in providing sufficient volumes to enable operating large pipelines **Electrolysers + Offshore wind:** Capacities infrastructure incentivize industry to produce volumes linked to refineries as demand sink	**Upscaling technologies and volumes:** GW-scale electrolysers and decommission SMR facilities if possible	**PSA:** Centralised PSA for SMR facilities still operating

Figure 72: *Transition pathway visualising general actions required for end-vision 3.*

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