Roadmaps to a hydrogen future in the Netherlands by 2050

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Executive summary

Countries are setting goals to limit climate change. With the Paris Agreement a global goal was set to reduce GHG emissions. The Netherlands aims to reduce GHG emissions by 95% by 2050 compared to 1990. Hydrogen is an alternative energy carrier that enables a clean future. In the Climate agreement, the Netherlands acknowledges potential for hydrogen to fulfil climate goals and become market leader in this area. Hydrogen shows potential for (1) carbon free feedstock for process industry, (2) carbon free energy carrier of high temperature heat in process industry, (3) energy storage and transport capacity to enable renewables, (4) transport, and (5) built environment. The presence of a natural gas grid is a driver for implementation of hydrogen.

While several studies have been conducted on the potential of hydrogen between 2000 and 2018 for the five hydrogen potentials, no large developments have occurred in the use of hydrogen. The demand for hydrogen stayed constant over the years only for use in the industry of ammonia production and (petro)chemical industry. This research aims to provide concrete roadmaps for hydrogen futures based on earlier studies, to explore the possibilities for hydrogen development. For this study, no new visions are created with workshops, but existing studies are compared and the key takeaways provide the input for visions. To develop actual roadmaps, a backcasting study has been conducted. Backcasting studies normally do not have prior visions. However, in this study backcasting has been implemented to explore concrete changes and actions that are necessary for development of hydrogen to fulfil the visions that resulted from the existing studies.

The results of the backcasting analysis are placed in time to form a roadmap for hydrogen visions. Key actors and policy measures are determined to realize the visions. The following research question has been formulated:

What are possible roadmaps to enable hydrogen futures in the Netherlands by 2050?

From the research question, the following results and conclusion can be made. First, hydrogen plays a role in industrial clusters in the Netherlands. Potential for future hydrogen markets strongly depends on the further development of the energy system and alternatives in the different sectors. Electrolysis and SMR with CCS to some extent are production methods to make hydrogen production cleaner. Depending on new markets, more stakeholders will become involved in the current hydrogen system. Based on existing visions and scenarios, three visions

have been constructed. The constructed visions are based on hydrogen as secondary energy carrier and hydrogen as primary energy carrier. Often hydrogen is compared to electricity.

Vision 1: All electric. Vision 1 describes a system where electricity is used as the primary energy source. Hydrogen plays an important role in flexibility of the energy system. Electrolysis has to be scaled to provide flexibility. Thus, support is needed for electrolysis in an early phase of the roadmap. The current production of grey hydrogen is after scaling of electrolysis replaced by green hydrogen. Scale is key to competitiveness of green hydrogen in the current hydrogen system. The key actors are utilities, TSO, electrolysis manufacturers and current hydrogen producers. Policy measures for electrolysis and storage infrastructure are used in this scenario.

Vision 2: One integrated system. Vision 2 describes a system where hydrogen and electricity are integrated. Hydrogen is implemented in built environment, industry for high temperature heating, heavy vehicle transport and inland navigation. Hydrogen production will change over time. In the beginning blue hydrogen is supported to reduce emissions of the current hydrogen production. After further development of markets and hydrogen, green hydrogen is promoted to replace the blue hydrogen production. In built environment a similar transition is constructed. In early stages hydrogen is promoted with simultaneous promotion of energy efficiency measures in built environment. At the end of the time period, energy efficiency measures have improved, and alternative heating systems can be implemented. The key actors are TSO, DSO, current hydrogen producers and utilities. From a policy perspective, timing with support for blue hydrogen and green hydrogen is key. First, blue hydrogen needs to be stimulated and by the time green hydrogen should be implemented, blue hydrogen has to become less favourable.

Vision 3: Go hydrogen. Vision 3 describes a system where hydrogen is implemented to its full potential. Every action is to enable a large hydrogen economy in 2050. While development and scaling are to improve the technologies and supply chain. In the maturation phase hydrogen plays an important role as primary energy carrier in the energy system. Especially in the early stage, demonstration and governmental support are necessary to realize a hydrogen future. The key actors are TSO, heat providers industry, DSOs, transport refuelling operators and hydrogen producers. The largest challenge for vision 3 is to facilitate the large growth of hydrogen supply, demand and need for infrastructure. With consistent policy strategies, the growth of hydrogen can be facilitated and not blocked.

From the three roadmaps and visions some recommendations can be formed for Gasunie & Tennet, DSOs and the government.

Gasunie & Tennet play an important role in the energy transition. Hydrogen may provide a solution for the challenges with first, hydrogen offers a great opportunity for Gasunie to retain the current t natural gas infrastructure. Though considerations on quality of the infrastructure should be considered. Second, In the current energy system, electricity and gas is not connected. With the development of power-to-gas, the electricity system and gas system may become interconnected.

Recommendation for DSOs relate to a potential increasing demand of hydrogen in built environment and the use of the current natural gas grid. First, with the current developments of hydrogen in public debate may lead to social pressure towards hydrogen in the built environment. DSOs in collaboration with regions and municipalities should be realistic of hydrogen in the built environment. Second, DSOs should look carefully in to the natural gas grid and elaborate on plans how hydrogen could be used in the grid.

Recommendations for the government relate to enabling hydrogen in future energy systems. While steps are taken to enable hydrogen, some additional actions can be taken. First, tenders and subsidies will reduce investment uncertainty. By setting certain targets of hydrogen implementation in sectors can reduce the investment uncertainty further. Second, keep monitoring technological developments. Hydrogen is for some application still in the development phase and not considered for application. Thrid, actively discuss the infrastructure with Gasunie and current hydrogen infrastructure operators. There are various ideas of how the infrastructure should be operated. Based on the development of the hydrogen market, different solutions should be implemented.

For further research, the approach of vision comparison could be further developed. The approach shows promising results, but the limitations should be further elaborated on. In other situations, for future energy systems, vision comparison could offer a solution in case many researches already have been conducted. Second, in this study technical, economic and environmental modelling have not been assessed. Modelling the visions may provide new insights in the pathways and roadmaps and may lead to differentiating quantification of the visions. Combining models with pathways studies may provide a better insight in the bottlenecks between technical possibilities and realisation of the vision. Third, only interviews have been conducted for this study. In future research, workshops could be conducted for a similar study to gain more detailed insights on roadmapping approach and to provide more platform between stakeholders.

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1 Introduction

In the 2015 Paris Agreement countries around the world agreed to collectively tackle the issue of climate change (United Nations, 2015). Countries agreed to aim for a well below increase of 2 degrees Celsius by reducing greenhouse gas (GHG) emissions by 2050 relative to 1990. In order to reach the target, countries are to a large extend investing in renewable energy sources (RES). In a projection it is expected that RES will account for 12.4% of the global energy demand in 2023 (IEA, 2018).

Though renewables are a clean source of energy, challenges occur with the increase of capacity. The main energy carrier for renewables is electricity (e.g. hydropower, bioenergy, wind and solar). An increase of renewable energy sources creates challenges for balancing of the grid and matching demand in seasonal fluctuations (Dickinson et al., 2017). A mix of energy carriers improves security of supply for future energy demands. Alternative energy carriers such as hydrogen may offer a solution.

In 2017 the Hydrogen Council (2017) announced a vision for the hydrogen economy in 2050 at the World Economic Forum. High potential for hydrogen is expected in the transportation sector, in the refining and production of methanol, in heating and powering buildings and industry, and as storage for renewable energy. For the hydrogen council scenario, a share of 18% hydrogen of the total energy demand by 2050 is expected. According to the Hydrogen Council, hydrogen can lead to a reduction of 20% CO_2 emissions contributing to the total CO_2 abatement needed.

In the Netherlands, the interest in hydrogen as an energy carrier is increasing as a result of the worldwide climate change developments. Under the Dutch Climate Agreement, it is aimed to reduce GHG emissions by 49% by 2030 compared to 1990 and 95% in 2050. The Dutch government states hydrogen is a key technology to less CO_2 emissions. The Netherlands has the potential to create a distinctive clean-tech-industry and knowledge position to proactive tackle the energy transition with its process industry, geographical advantages, gas knowledge and gas infrastructure (Klimaatberaad, 2018). Both the climate goals and potential to become a market leader in clean-tech-industry, drive the further development of hydrogen systems in the Netherlands. From October 2018 on a subsidy scheme of 2.2 million euros has opened that supports innovative projects with hydrogen as energy carrier.

1.1 Problem statement

As illustrated, there is a multitude of long-term plans for hydrogen with different expatiations.

The hydrogen system is a socio- technical system with many stakeholders involved. A transition towards an energy system with hydrogen asks for changes in technology, economics and politics. A combination of factors will influence the increase in share of hydrogen by 2050. Still research is needed to understand the functioning of hydrogen in the energy system and to understand how technologies will further develop. Analysing a socio- technical system matches skills learned in the curriculum of CoSEM.

This research aims to define three roadmaps for hydrogen in the Netherlands by developing visions for 2050 based on the potential of hydrogen. The visions will lead to matching pathways that focus on reaching a GHG reduction of 80-95% by 2050. The visions allow for hydrogen integration from primary energy carrier to secondary energy carrier. Both national and international factors will be taken into consideration for developing the pathways. A new approach for vision construction is issued to use existing literature and reports to define essential factors for hydrogen futures in the Netherlands. Furthermore, this research aims to reveal how a (combination of) factors may influence the implementation of hydrogen in the Netherlands. Stakeholder involvement and policy measures are taken in consideration to determine those factors.

1.2 Literature overview

This section discusses literature on the future of hydrogen. A search has been done in Scopus and further literature is found trough the snowballing method for studies on hydrogen futures. The search term is as follows ‘Hydrogen AND (Future OR scenarios OR backcasting OR Pathways)’.

1.2.1 Hydrogen economy

A hydrogen economy means hydrogen is the main energy carrier in the energy system with hydrogen as the key energy carrier (Gosselink, 2002). The future of hydrogen is strongly dependent on the demand of hydrogen and the technological development of hydrogen technology (Hetland & Mulder, 2007). Hydrogen shows potential as an energy carrier of the future and even as an energy source for consumption (Mazloomi & Gomes, 2012). Interest in hydrogen changes in time (Figure 1). In the period of the Kyoto Protocol an increase of hydrogen visibility was noticed. Currently, hydrogen is getting back in visibility.

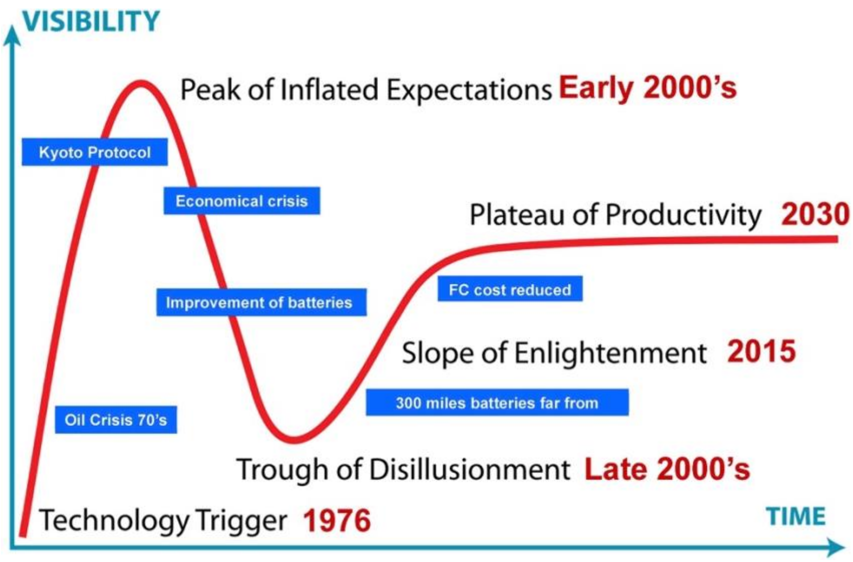

Figure 1 - Hype cycle for the evolution of visibility of the hydrogen economy versus time. (Moliner, Lázaro, & Suelves, 2016)

In the debate of the future of hydrogen, hydrogen is often compared to electricity. Barber (2005) and Shinnar (2003) favour the use of electricity over hydrogen, because energy losses occur in hydrogen systems. While hydrogen is expected to become an important energy carrier after 2050 (Marchenko & Solomin, 2015), Hosseini & Wahid (2016) argue development of hydrogen is strongly dependent on electricity and fossil fuel costs; at the moment hydrogen is more expensive than electricity and fossil fuels.

Others have mentioned integration of the two economies (hydrogen and electricity) (Gosselink, 2002; Marchenko & Solomin, 2015). Gosselink describes a sustainable market, where both renewable hydrogen (green hydrogen) production and green electricity are interconnected in one market. Marchenko & Solomin argue hydrogen and electricity should be a combined economy and not a decision between one or the other.

1.2.2 Hydrogen futures

In global scenarios the role of hydrogen differs strongly. Shell's (2013) New Lens Scenarios highlights hydrogen infrastructure will be developed globally and used for energy storage and transportation, produced by renewable sources on the long term. From 2035 hydrogen and electricity transport will increasingly infiltrate road transport. On the other side, one of the scenarios states that the transition towards green hydrogen will take slowly, coming from production based on coal and gas, since electrolysis is still expensive. The two scenarios show different outcomes for a hydrogen future. In A Clean Future for all (European Commission, 2018) it becomes clear that with a large infiltration of hydrogen, the total electricity demand will increase. Hydrogen will by 2050 play an increasing role in transport and industry, while hydrogen storage is limited. Hydrogen is expected in many scenarios to play a small role in reaching climate change goals under the Paris Agreement with a share less than 10% for 2050 until 2100 (Gambhir, Rogelj, Luderer, Few, & Napp, 2019). Though hydrogen has a small share through scenarios, the future of hydrogen may still be important in decarbonizing gas grids and heavy transport sector where it performs better than electrification.

From global scenarios it can be concluded several indicators influence the development of hydrogen according to Hennicke & Fischedick (2006). They argue that first, there is not one answer how the hydrogen economy will look like, many potential scenarios are issued. Second, increase of efficiency is a prerequisite for implementation of hydrogen. Third, outcomes for hydrogen may strongly differ between countries due to its circumstantial situation. In detail studies are needed on national and local level.

In various countries scenario analysis for hydrogen have been conducted. From country specific studies some elements are often highlighted for being important for further development of hydrogen. Those elements are development of infrastructure, green hydrogen production, hydrogen storage capacity to facilitate transition, potential of fuel cell vehicles, hydrogen injection in gas infrastructure and expected low integration of hydrogen before 2030 (Hennicke & Fischedick, 2006; Le Duigou et al., 2013; McKenna et al., 2018; Rodríguez et al., 2010; Ruhnau, Bannik, Otten, Praktiknjo, & Robinius, 2019; Silva, Ferreira, & Bento, 2014; Sørensen et al., 2004; Viesi, Crema, & Testi, 2017).

1.2.3 Scenarios Netherlands

Hydrogen in the Netherlands has been described from 2000 onwards (Table 1). Up to 2011 hydrogen was mentioned in many studies. Between 2011 and 2017 hydrogen was not included in studies, while in increase of hydrogen studies can be seen after 2017. While the debate has increased in the Netherlands from 2000 and onwards, since then not much has changed regarding hydrogen integration in the current energy system.

Early studies described potential visions for hydrogen in the Netherlands often focussed on transport and hydrogen in built environment. In 2006 a study was conducted by Werkgroep waterstof (2006) that led to an integral vision for hydrogen in the Netherlands. Transition pathways and goals were identified. In 2007 a participatory backcasting study was conducted (Hisschemöller, Bode, van de Kerkhof, & Stam, 2007). The study first identified three visions based on the repertory grid method that allowed to construct visions based on common notions (van de Kerkhof, Cuppen, & Hisschemöller, 2009). As a result of the study five key institutional factors were identified that shape the further development of hydrogen in the Netherlands, namely (1) physical infrastructure, (2) centralized versus decentralized system, (3) the dominant knowledge system, (4) policy approach, and (5) lack of knowledge competition. Later in 2011 PBL (2011) conducted a study in combination with ECN where different routes towards a clean economy in 2050 is discussed. The role of hydrogen is mentioned to convert surpluses of electricity to hydrogen where it can function as energy carrier.

More recent research and reports show an increasing interest in hydrogen. Two regional studies have shown the potential for hydrogen in the Northern part of the Netherlands and the province Zuid-Holland (Noordelijke Innovation Board, 2017; Wijk, Rhee, Reijerkerk, Hellinga, & Lucas, 2019). While the last report so far consists of a vision document, the project in the Northern Netherlands has constructed an investment agenda for hydrogen.

Other scenario studies for the Netherlands show increasing potential for hydrogen with the creation of a hydrogen economy besides electricity (CE Delft, 2018; Gasunie & Tennet, 2019; Ouden, Graafland, & Warnaars, 2018).

1.2.4 Barriers for hydrogen

In literature barriers for hydrogen are often mentioned as a drawback in further development for hydrogen in energy systems.

McDowall & Eames (2006) acknowledge without large changes hydrogen will emerge slowly or not at all. The barriers for hydrogen are absence of a hydrogen refuelling infrastructure, high costs, and technological immaturity. Without strong governmental support, major changes in social values or technological development, and changes in climate change hydrogen will not emerge with a strong speed.

Infrastructure is a barrier for hydrogen implementation (Konda, Shah, & Brandon, 2011). On the other hand, it is suggested the natural gas infrastructure can be used for hydrogen with some adjustments. Shinnar (2003) criticizes using the infrastructure of natural gas for hydrogen, because pipeline volume needs to be increased and transport losses increase what makes to overall infrastructure less efficient. Dunn (2002) argues in contrary the costs for hydrogen are perceived as high, because the natural gas infrastructure shows large potential and with slow integration hydrogen could become cost competitive.

Furthermore, many pathways for hydrogen will ask for a high level of collaboration between different actors such as industry and government (Mcdowall, 2014). Managing this is highly uncertain.

1.2.5 Overview knowledge gaps

The role of hydrogen in future energy systems is highly uncertain. Form the literature review the following knowledge gaps can be summarized matching uncertainty around future hydrogen:

- Over the last couple of years many studies and reports conducted on the potential of hydrogen in both Europe and the Netherlands. The studies have not yet led to an altering use of hydrogen. How can earlier studies provide guidance in future development of hydrogen.
- Global debate on hydrogen economy still strong. Interest in Netherlands increasing again. Uncertainty to what extent hydrogen will become part of the Dutch energy system and to what extent it will be integrated with the energy system of other energy carriers.
- Several barriers for hydrogen are identified. How to overcome the barriers is not analysed in both literature and reports, while overcoming barriers is crucial in further development of hydrogen.

Although the debate on hydrogen is still going on, the Netherlands seems to be rather positive on integration of hydrogen. Pathways towards a hydrogen future are unknown and stakeholders have no idea how markets will develop and how to overcome the barriers of implementation. The Netherlands may have another potential for hydrogen due to its geographical locations, existing infrastructure for natural gas and the fact that natural gas is phased out of households. Without incentives to overcome the barriers, hydrogen will not accelerate under business as usual.

1.3 Research questions

To gain a deeper understanding on the role of hydrogen in 2050 and how to get there, research is needed. Therefore, the research question is as follows:

What are possible roadmaps to enable hydrogen futures in the Netherlands by 2050?

Sub question are formulated to answer the main research question. The sub questions are defined as follows:

1. What are developments, challenges and stakeholders of the current hydrogen system in the Netherlands?
2. How can similarities and differences of existing visions a provide potential visions for hydrogen in future energy systems in the Netherlands by 2050?
3. What are visions and roadmaps for hydrogen futures in the Netherlands by 2050?
4. What are implications of the roadmaps for actors, potential responses and policy strategies to overcome barriers in roadmaps to reach the desired outcome?

1.4 Research Approach

For this research, a scenario approach is used. Within future studies, scenarios are a common way to describe possible futures. Many different categories of scenarios exists (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). For this research a normative approach is used. Normative scenarios are based on the question how different targets can be reached. The starting point of normative scenarios is the focus on a certain future situation or objective followed by how it should be realised.

To answer the research question, a backcasting analysis is used, because the future of hydrogen is highly uncertain. Backcasting is a normative scenario approach. Backcasting is often used when goals are unreachable with the current developments (Börjeson et al., 2006). Backcasting is seen as a useful approach when there is a complex societal problem, need for major change, dominant trends influence the problem, externalities are not yet solved in the market and long-time horizons allow for other solutions to develop in time to solve the problem (Dreborg, 1996). In case of hydrogen, the current regime with fossil fuels needs to be changed, thus hydrogen can play a role in solving the problem of climate change. Technological, economical and societal changes have to take place before hydrogen will become a part of the regime.

Backcasting is a qualitative analysis where goals are determined. The goals often represent a desirable future. From there a backwards analysis is used to research what is needed to reach the goals as described by Quist (2007). The outcome of the approach are pathways towards the set goals.

From the literature review it became clear technological development and market creation must be created alongside. Furthermore, collaboration between different stakeholders strongly influence the outcome of this mutual development. Therefore, a strong focus will be on the role of stakeholders for the potential of hydrogen. Quist (2007) purposes a methodological framework for participatory backcasting. The framework entails a five-stage approach with different tools for stakeholder involvement, future visions and analytical results. Involving stakeholders is important, because they will have to realise the proposed actions and follow-up from the different pathways. Tools and methods that can be used in the five stages are related to stakeholder participation, design and development, and analysis. Analysis tools are used to assess the scenarios and designs (Quist, 2007).

In backcasting study the construction of visions is done by workshops and interviews. In case of hydrogen in the Netherlands many studies have been conducted and an approach of visions comparison is used based on PESTLE elements as described by (Figueroa, de Groot, van Paassen, Park Lee, & Regett, 2013). Using vision comparison is an adjustment to the existing theory. Furthermore, the outcome of backcasting studies are often pathways. This study takes the backcasting approach to a next level with roadmaps where actions are placed in time. The roadmaps allow to identify bottlenecks and drivers. From there actor involvement and policy instruments can be determined based on (Hughes, 2013).

A disadvantage of backcasting is the lack of a quantitative analysis. To resolve this, analysis tools can be used. Implementing the goals for hydrogen provides insights in demand for electricity and other sources, dependent on the production of hydrogen. A barrier for participatory backcasting is stakeholder engagement through the process. This can be resolved by making the backcasting framework independent of stakeholder participation by integrating it with other backcasting frameworks and using other methods to gain results. Stakeholder involvement can be used as validation of found results.

1.5 Overview chapters

In the remainder of the thesis the main research question will be answered. First chapter 2 Literature background provides insight in the theories and literature used for this thesis. Chapter 3 Research approach & methodology elaborates on methods and theories used to conduct the research and how data is gathered. The results are discussed in chapter 4 System orientation, chapter 5 Visions for hydrogen in 2050, chapter 6 Backcasting and chapter 7 Pathways & roadmapping. Finally the results are discussed in chapter 8 Discussion and concluded in chapter 9 Conclusion.

2 Literature background

The literature background provides insights and in-depth analysis of frameworks used. The aim of the chapter is to argue why certain decisions and adjustments have been made as a basis for the research. First transitions in socio-technical systems is described in section 2.1 followed by future studies in section 2.2. Next in section 2.3 visions and visioning are explained. Section 2.4 describes backcasting. Section 2.5 elaborates on socio-technical scenarios. At last, section 2.6 provides a conclusion on the literature background

2.1 Transition in socio-technical systems

Energy system are often described as socio-technical systems. Transition theory focusses on socio-technical systems what consist of actors, institutions, material artefacts and knowledge (Markard, Raven, & Truffer, 2012). The elements interact leading to a specific service for society. A socio-technical transition occurs when a set of processes are changed in the socio-technical system. Often transitions take place over a long period of time.

A field of research on transition towards sustainability has emerged under political and socio-science interest (Markard et al., 2012). The frameworks that have emerged over time are transition management (TM), strategic niche management (SNM), multi-level perspective (MLP) and technological innovation systems (TIS).

The MLP framework allows to study transition through multiple levels and therefore is further explained for this research. The MLP allows for a simplified and organized analysis of a complex transition towards a sustainable future (Smith, Voß, & Grin, 2010). The MLP analyses transition as a non-linear process through three analytical levels: socio-technical landscape, socio-technical regime and niche-innovations (Geels, 2011).

2.2 Future studies: Scenarios

Future studies help organisation to develop strategies for dealing with complex and uncertain futures (Ligtvoet et al., 2016). In the field of future studies, many studies and approaches exist of which scenarios is one approach (Börjeson et al., 2006). Scenarios are a common way approach for companies and research as a basis for strategic planning (Dreborg, 1996). Scenarios allow for a broader analysis and the use of different scenarios allows to cope with uncertainty.

Börjeson et al. (2006) categorize the following types of scenarios, namely predictive, explorative and normative (Figure 2).

Predictive scenarios are used to generate a plan based on expected situations. Two different types of predictive scenarios are forecast and what-if scenarios. Both types try to predict the future under likely developments and conditions under certain events. Explorative scenarios are based on what can happen in the future. Two types of explorative scenarios can be distinguished: external and strategic scenarios.

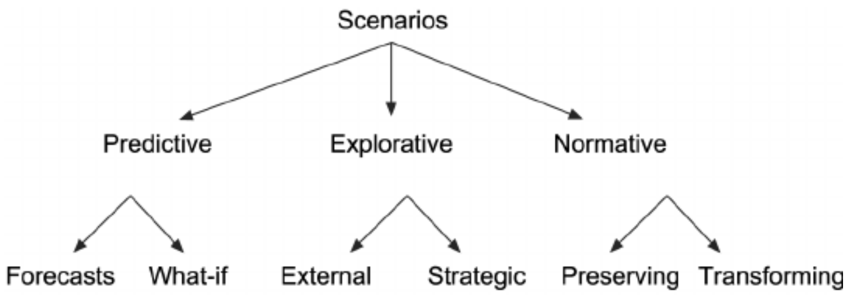

Figure 2 - Scenario typology (Börjeson et al., 2006)

Several perspectives are considered to determine the possible outcomes. Possible outcomes and policy measures are taken into consideration in the outcome of the scenarios. Normative scenarios are based on the question how different targets can be reached. The starting point of normative scenarios is the focus on a certain future situation or objective followed by how it should be realised. Two types of normative studies are preserving scenarios and transforming scenarios. Preserving scenarios create scenario on the principle the target can be reached by adjustments to the current system, while transforming scenarios reaching the targets when the current system blocks change. Backcasting is an example of a transforming scenario approach. Often predictive approach and exploratory approach are used (Quist, 2016). Normative scenarios are used to formulate 'alternative' futures instead of desirable futures (Quist, 2016).

2.3 Visions and Visioning

In scenarios often the future is constrained by activities and motivations of actors in the current system and actors may be less open to radical changes in the system (Hughes, 2013). Visions broaden the scope to how the system could look like without the limitation of the current socio-technical system. In case more actors support a vision and begin to act accordingly, the vision becomes more realistic. Visions can act as an input for actor behaviour and thus change the current system (Hughes, 2013; Wiek & Iwaniec, 2014). The process of actors seeing opportunities in the vision and acting upon it leads to diffusion of the vision (Quist, 2016).

Wiek & Iwaniec (2014) provide a framework for quality criteria and design guidelines for sustainable visions. Quality criteria of a vision are that a vison should be visionary, sustainable, systematic, coherent, plausible, tangible, relevant, nuanced, motivated and shared. Figure 3 summarizes the quality criterion with the key features.

In order to align the key features in a normative vision, the visions should be constructed consistent of three elements (William McDowall & Eames, 2007):

- Narrative description of the hydrogen system.
- Technology deployment is expressed in quantitative indicators.
- System diagrams that represents the vision.

The three elements will provide a well-rounded storyline for visions in future studies.

Table 1 Key features and sources of the quality criteria for sustainability visions

	Quality criterion	Key features	Sources
1	Visionary	Desirable future state; with elements of (aspirational) surprise, utopian thought, far-sightedness, and holistic perspective	Dreborg (1996); Höjer and Mattsson (2000); Raskin et al. (2002)
2	Sustainable	In compliance with sustainability principles; featuring radically transformed structures and processes	Holmberg and Robèrt (2000); Newman and Jennings (2008)
3	Systemic	Holistic representation; linkages between vision elements; complex structure	Meadows (1996); Bossel (1998); Raskin et al. (2002)
4	Coherent	Composed of compatible goals (free of irreconcilable contradictions)	Wiek and Binder (2005); Potschin et al. (2010)
5	Plausible	Evidence-based—informed by empirical examples, theoretical models, and pilot projects	Wright (2010); Wiek et al. (2012)
6	Tangible	Composed of clearly articulated and detailed goals	Ravetz (2000); Wiek and Binder (2005)
7	Relevant	Composed of salient goals that focus on people, their roles, and responsibilities	Cash et al. (2003); Wangel (2011); Wiek and Larson (2012)
8	Nuanced	Detailed priorities (desirability)	Trutnevyte et al. (2011); McDowall and Eames (2007)
9	Motivational	Inspire and motivate towards the envisioned change	Swart et al. (2004); Smith et al. (2005); van der Helm (2009)
10	Shared	Display a critical degree of convergence, agreement, and support by relevant stakeholders	Smith et al. (2005); van de Kerkhof (2006); Krütli et al. (2010); Quist et al. (2011)

Figure 3 - Overview of key features and sources of the quality criteria for sustainability visions.

2.4 Backcasting

In backcasting studies an alternative future is envisioned that deviates from the existing system and expected future (Giurco, Cohen, Langham, & Warnken, 2011). Sustainable development has raised the need for evaluation of future prospects for economic and environmental development over the long-term (Robinson, 1990). Where forecasting studies can only predict the most foreseeable future as a result of embedded assumptions and current events, backcasting allows to explore desirable futures, where major adjustments are needed. Policy is driven by scientific findings on environmental issues with an increasing public demand. In terms of sustainable development backcasting can lead to strategic processes to reach sustainable goals, identify actions for transitions and provide tools to monitor progress. Backcasting is seen as a transforming scenario approach. The characteristics of a transforming scenario approach are that scenarios are often qualitative with quantitative elements, often over a very long time and the system structure is changing (Börjeson et al., 2006). Dreborg (1996) specifies 5 characteristics for a backcasting study:

- The problem of the study should be complex, affecting many sectors and levels of society
- In the study there is need for major change. Small adjustments to the system will not be sufficient to solve the problem.
- Change is limited to a great extent by dominant trends.
- The problem is partly a matter of externalities that cannot be internalized by the market.
- The time horizon is long enough that major changes in the system can take place.

Many approaches have been designed in backcasting literature. Backcasting can be distinguished as design-orientated backcasting and participation-orientated backcasting (Quist & Vergragt, 2006; Wangel, 2011). Within design-orientated backcasting distinguish can be made between target-oriented, pathway-oriented and action-oriented backcasting. Emphasis in target-oriented is on fulfilling the goal. Pathway-oriented places emphasis not on a set target, but on the path towards sustainable development, because of its changing nature. Action-oriented aims to develop an action plan or strategy, limited to predetermined set of actors. In participation-orientated backcasting emphasis is on the outcome of participation over the backcasting methodology

Four backcasting approaches are broadly discussed in literature:

- Robinson's (1990) backcasting approach
- The Natural Step backcasting approach (TNS) (Holmberg, 1998; Holmberg & Robert, 2000)
- Sustainable technology development (STD) (Weaver, Jansen, van Grootveld, van Spiegel, & Vergragt, 2000)
- Participatory backcasting (Jaco Quist, 2007)

As a basis of this research, participatory backcasting is further explained.

2.4.1 Participatory backcasting

Traditionally backcasting approaches explored energy futures and the potential for policy analysis. The approaches are very design-orientated. Later on, more emphasis was placed on the involvement of stakeholders and the fact there is continuous feedback between future visions and present actions (Quist & Vergragt, 2006). An interactive and iterative process is created. From the analysis of Quist (2007) three key elements of participatory backcasting can be selected (Quist, 2013; Quist, 2016):

- Construction and use of desirable future visions or normative scenarios
- Strong stakeholder involvement integrated with stakeholder learning processes.
- Using a wide range of methods: process, participation, analysis and design.

Table 7.3 Overall scheme for backcasting

Step 1: Strategic problem orientation	
1A	Setting requirements/criteria, basic assumptions, process plan, methodology.
1B	System and regime analysis.
1C	Stakeholder analysis.
1D	Trend and problem analysis.
Step 2: Generating future visions	
2A	Detailed (normative) standards/criteria and targets.
2B	Idea articulation and elaboration.
2C	Generation of one or several visions.
Step 3: Backcasting analysis	
3A	WHAT–HOW–WHO analysis part 1: WHAT are the (technological, cultural-behavioral, organizational and structural-institutional) changes?
3B	WHAT–HOW–WHO analysis part 2: required actions and stakeholders.
3C	Drivers and barriers analysis.
Step 4: Elaboration and follow-up agenda	
4A	Scenario elaboration (e.g., turning vision into quantified scenario).
4B	Scenario sustainability analysis.
4C	Generation of follow-agenda and proposals.
4D	Develop transition pathway.
Step 5: Embed results and stimulate follow-up	
5A	Dissemination of results and policy recommendations.
5B	Stimulate follow-up activities.
5C	Stakeholder learning evaluation.

Figure 4 - A methodological framework of participatory backcasting (Quist, 2016)

The three elements have led to a five-step framework with a strong involvement of stakeholder, their knowledge and values. Quist (2016) provides an overview of the 5 steps with sub steps to be considered (Figure 4).

Similar to other backcasting approaches, the first step is strategic problem orientation. Strategic problem orientation entails exploring the problem from a systematic view. Normative assumptions, requirements and targets are defined. The orientation forms a basis for the development of future visions. Future visions are social constructs which are highly dependent on actor endorsement (Quist & Vergragt, 2006). Several participatory methods are used to develop visions, such as brainstorm sessions, morphological analysis and Q-methodology (Quist, 2016). After the vision is developed, the question what changes are needed to bring about the future vision. WHAT-HOW-WHO questions are raised. The WHAT question raises on what needs to change in order to reach the vision, the HOW question raises question on how the change should take place and the WHO question answer who could change or who should be involved in change (Wangel, 2011b). With the found changes, actions and pathways can be determined. As a final step action agendas and follow-up strategies can be created for the different actors.

2.4.2 Including actors and governance

Wangel (2011a) criticises backcasting on the limitation of actors and governance. While participatory backcasting is increasing, actor involvement does not necessarily mean presence actors in resulting scenarios. Furthermore, often WHAT and HOW questions are asked, but WHO question is not always included in the backcasting analysis. Actor involvement is necessary for the next step, including governance. Governance can be seen as the attempt to achieve the desired outcome. Four approaches are discussed to include actors and governance:

- Stakeholder analysis approach
- Social network approach
- Governance model approach
- Policy and change approach

As part of governance model approach and policy change approach a process diagram can be used to study the vision in terms of process of change. The diagram covers the pathway from one system to another system and there is as strong reason to include prerequisites such as institutions and previous decisions. The end-use phase facilitates to reflect on long-term management and the time scope of change. When highlighting the interactions between activities in order to reach the vision, key decision points can become visible.

2.4.3 Vision comparison and selection

Often visions are generated with interviews and workshops with many experts and stakeholders in backcasting studies. In case many visions are available in literature, construction of new visions might not be necessary. Comparison and selection techniques are necessary to construct visions.

When comparing visions, key elements of the system for each vision should be taken in consideration. Key elements can be determined in a system and technological analysis (Giurco et al., 2011). The PESTE framework allows for structured comparison of the existing visions (Figueroa et al., 2013). PESTE takes five aspects in consideration: Political, Economic, Social, Technical and Environmental. An additional aspect, legal, can be included leading to a PESTLE. Visions can be analysed on those aspects and allow for consistent comparison. will be analysed based on those aspects. A systematic approach in comparing visions enables clustering visons and highlighting differences.

Selection criteria allow for distinguishing between visions. McDowall & Eames (2007) defined criteria for scoring scenarios. Scenarios are scored on environmental, economic, social, energy security and other criteria. The criteria were scored on importance by participants before the visions were analysed.

2.5 Socio-Technical Scenarios

Socio-technical scenario (STSc) is a method to research transitions in future scenarios. The method builds upon transition theory, where the socio-technical landscape, socio-technical regime and technological niche form the centre of transitions. STSc has been developed by Elzen, Geels, & Hofman (2002) from the MLP where historical transitions are analysed (Foxon, Hammond, & Pearson, 2010). STSc allows to research future transition based on transition theory. Besides technological development, STSc considers links between (1) various options, how developments affect and are affected by strategies, and behaviour of stakeholders (Foxon et al., 2010).

STSc, as proposed by Elzen et al. (2002), consist of a few central tasks that will help to create scenarios. First, the current socio-technical regime has to be characterized in terms of the key elements of a regime. Second, potential technological niches should be identified with their characteristics. Third, factors in the main socio-technical landscape should be identified that influence the dynamics in niches and regime. The final task is to design choices at the landscape level and niche level. Factors are chosen that will scope the macro-environment and niches are selected that will be able to become part of the regime.

In research, STSc methods have been further developed and in some cases combined with quantitative approaches (Foxon, 2010; Geels, McMeekin, & Pfluger, 2018; Hughes, 2013; Mcdowall, 2014).

Foxon et al. (2010) describe three main steps for identifying the initial outline of transition pathways:

- Characterise the existing energy regime.
- Identify dynamic processes at the niche level.
- Specify interactions giving rise to or strongly influencing transition pathways.

Foxon (2013) combined the initial outline of transition pathway with a quantitative model to further research the technological feasibility, social acceptability and sustainability appraisal of the pathways.

Hughes (2013) identifies three main types of scenario approaches: (i) trend based, (ii) actor based and (iii) technical feasibility. Combining the three types of scenario approaches can guide short term decisions to reach long term goals and benefits from actor-based system views. This results in an iterative framework where visons, actor network and technological network are combined (Figure 5)(Hughes, 2013). When dealing with uncertainty in scenarios, it is important to consider three kinds of future elements: pre-determined elements, actor-contingent elements and non-actor contingent elements (Hughes, Strachan, & Gross, 2013). Pre-determined elements and non-actor contingent elements cannot be influenced by actor decisions. Actor-contingent elements can be affected by choices made by actors in the system and therefor can be influenced by proactive decision making. Different system decision caused by varying actor preferences can lead to many pathways due to many branching points (Mcdowall, 2014). Visions of actors can strongly vary and their preference for different pathways varies as well. Action of the different actors and decisions they make will in the end lead to a certain pathway. In case a normative objective is tried to be reached, actions can be analysed (decisions of actors) for a pathway towards the objective.

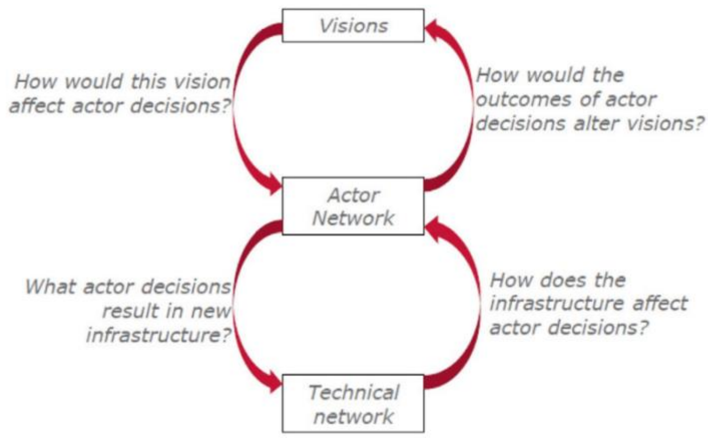

Figure 5 - 3 level iterative framework between vision, actor network and technical network (Hughes, 2013)

Geels et al. (2018) proposes a methodology with socio-technical qualification of model-based scenarios with the introduction of transition bottlenecks (Figure 6). Transformative action and policies take place trough time to alter the expected end point to the sustainable development goal.

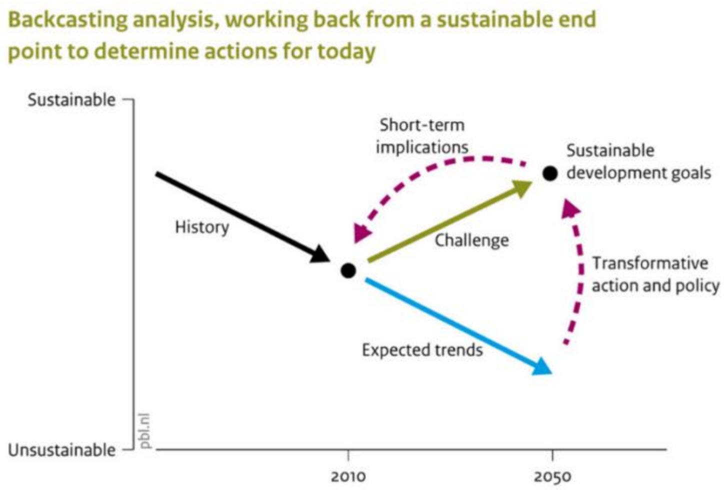

Figure 6 – Transitions from historical trajectories towards sustainable futures. (van Vuuren et al., 2015)

Often MLP-based analysis highlights the lack of transition do to locked-in regimes and not yet well-developed niche-innovations, while model-based scenarios lead to transition pathways of what should happen. The tension between what should happen and what is embedded in the existing system are transition bottlenecks. Including socio-technical transition theory supports to develop plausible pathways that can overcome transition bottlenecks.

2.6 Conclusion literature background

Quist's participatory backcasting frameworks forms the backbone of this research. The presence of existing visions could be seen as a reason for not using a backcasting study. Though the visions have not let to alternating usage of hydrogen and the study for hydrogen futures matches the 5 specifications for a backcasting study of Dreborg (1996). Thus, a backcasting approach has been chosen where visions form the basis of this study. The five steps in the backcasting approach are adjusted with aspects of the literature background.

First, Quist's framework uses workshops and other participatory methods to construct visions. An alternative method has been created based on PESTLE elements. The alternative method has been designed for the existence of multiple studies on hydrogen in the Netherlands where many stakeholders for hydrogen have been involved in. Existing studies are analysed based on PESTLE-elements and concluded in one final factor analysis that provides the input for vision construction and selection.

Second, Quist's framework step 4 and 5 focus on development of transition pathway and follow-up of the visions. The results of the backcasting study can be further elaborated on in research. From the literature background, literature on socio-technical scenarios has been found that can provide a more in-depth analysis of the final steps for backcasting studies. The findings of the backcasting study are organized in a follow-up agenda. For this research, emphasis is placed on the agenda as a roadmap for hydrogen transitions. Foxon (2010) introduces steps to further identify the transition pathways for various visions. Hughes (2013) introduces an iterative framework where the relations between visions, actor network and technical network can be analysed for various visions. Both frameworks are added to Quist's framework to provide a more in-depth analysis of those dynamics. The framework of Hughes provides strong actor involvement in later stages of vision implementation in roadmaps, which is not yet emphasized on in the later steps of Quist's framework. The roadmaps will provide detailed information with actions in time. The barriers and bottleneck as identified in the process of Quist's backcasting and Geels et al. (2018) provide the basis for determining matching policy instruments to overcome them.

3 Research approach & methodology

This chapter will elaborate on the different research methods and tools used in every stage. Each stage is discussed separately, since a wide variety of research methods are used.

The literature background forms the basis of the framework and methodology used for this research (Figure 7). The framework is based on the steps of backcasting methodology and transition theory. The framework can be divided in two phases: (1) the vision phase and (2) the roadmap phase. The vision phase provides knowledge on the system as a basis to construct visions. The pathway phase combines backcasting, transition pathway and roadmapping approaches to understand how visions can be achieved. The pathways highlight bottlenecks for the visions, while roadmaps provide solutions how to overcome the bottlenecks. Figure 8 summarizes how the different steps relate to time and level of sustainability. From the present system, a goal is set in the future (the desired future). With backcasting, objectives can be determined how the desired future will be reached in a certain transition pathway. Roadmapping allows to analyse how steps can be taken to go from the expected outcome to desired future and what actions are needed for that.

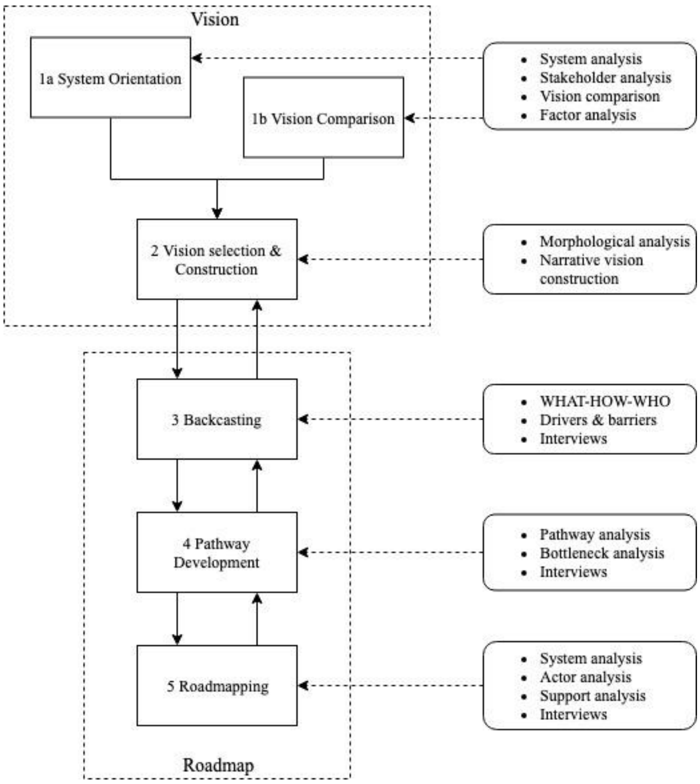

Figure 7 - Framework combining elements backcasting and socio-technical scenarios.

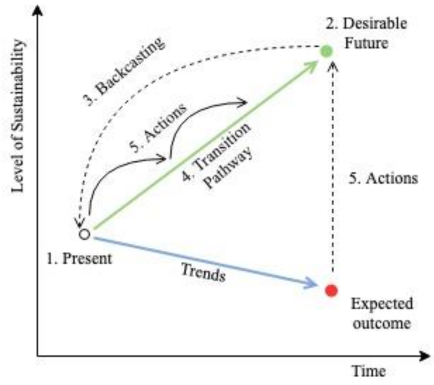

Figure 8 – Combining backcasting and pathway theory to a sustainable future. This figure is designed for the purpose of this research.

3.1 Stage 1: System orientation

Stage 1 focusses on exploring the problem from a systematic view. Normative assumptions, requirements and targets are defined. Four different analysis are used to orientate the existing system, namely (1) system analysis, (2) stakeholder analysis, (3) vision comparison and (4) factor analysis. The input data for the system orientation stage is gained with desk research from academic literature and reports. Each analysis will be explained in more detail.

The first analysis, i.e. system analysis, helps to structure and visualize the current system of hydrogen in the Netherlands. The system analysis will consist of six steps to set the scope of the current system as described by Enserink et al. (2010) with necessary adjustments:

1. Set the initial problem demarcation and level of analysis
2. Describe the current system
3. Describe potential adjustments to the current system
4. Provide quantitative summary of the current system with potential for hydrogen.
5. Provide an overview of the problem area using a system diagram
6. Define key elements for future systems

A system diagram, step 5 of system analysis, is used to structure the various components of a hydrogen system. Different components of the system will be determined, what will lead to a set of key components for a hydrogen system (step 6 of system analysis), which can be taken into consideration in the comparison of existing visions.

The second analysis, i.e. stakeholder analysis, identifies actors involved in the system, what actions and obligations they have in the system and how strongly they influence the system. Actors strongly influence the system and the components of the system analysis are performed by actors. With an increase of hydrogen in the system, more stakeholders could become important. Therefore, a distinction is made between the current stakeholder system and potential stakeholders for the system. Stakeholder analysis is conducted according to Hermans (2010) steps for stakeholder analysis:

1. Formulation of a problem as a point of departure
2. Inventory of actors involved in current system
3. Inventory of actors involved in future system
4. Determining the interests, objectives and problem perceptions of actors
5. Identify the interdependencies between actors by making inventories of resources and the subjective involvement of actors with the problem.
6. Determining the consequences of these findings with regard to problem formulation

Step 2 of stakeholder analysis allows for identification of stakeholders in the current system as a result of the system analysis. Step 3 of stakeholder analysis is an additional step that provides identification of stakeholders for potential future system. Some actors may be identified as a result of vision comparison. The identification of potential future stakeholders will be needed for development of pathways and roadmaps in later stages of research.

The final two analysis are visions comparison and factor analysis. Existing visions are analysed and compared. Several studies have been conducted in a period between 2000 up to now. Table 1 provides an overview of analysed studies.

Selection of studies has been done by searching for reports on hydrogen in the Netherlands and Europe. Studies that included hydrogen in future scenarios where included. Most studies are focussed on the Netherlands solely, however two studies have been concluded on a European level. In addition, two studies have been selected that focus on a local level (Zuid-Holland and Northern Netherlands). Visons are compared on key elements, actors and PESTLE-indicators. The key elements are a result of the system analysis. In case actors are mentioned in the existing visions, they will be summarized in the analysis. The PESTLE framework allows for structured comparison of the existing visions. Furthermore, quantitative results of the visions are summarized. Based on the PESTLE-analysis and quantitative summary existing visions can be compared and categorized when components align or differ. The overall results of the current system and vision comparison are summarized in a factor analysis based on PESTLE.

Table 1 - Overview studies for vision comparison

Report	Reference	Title	Focus year	Scope
Platform Nieuw Gas	(Platform Nieuw Gas - werkgroep Waterstof, 2006)	Waterstof Brandstof voor transities	2050	The Netherlands
Hisschemöller	(Hisschemöller et al., 2007)	H2 Dialoog	-	The Netherlands
PBL	(Planbureau voor de Leefomgeving (PBL), 2011)	Naar een schone economie in 2050: routes verkend	2050	The Netherlands
Noordelijke Innovation Board	(Noordelijke Innovation Board, 2017)	The Green Hydrogen Economy in the Northern Netherlands	2030	The Northern Netherlands
Berenschot	(Ouden et al., 2018)	Elektronen en / of Moleculen	2050	The Netherlands
European Commission	(European Commission, 2018)	A clean planet for all	2050	Europe
TKI Nieuw Gas	(Gigler & Weeda, 2018)	Contouren van een Routekaart Waterstof	2050	The Netherlands
Fuel Cells & Hydrogen Joint Undertaking (FCH)	(FCH, 2019)	Hydrogen Roadmap Europe	2050	Europe
Provincie Zuid-Holland	(Wijk et al., 2019)	Naar een groene waterstofeconomie in Zuid-Holland. Een visie voor 2030	2030	Zuid-Holland
Gasunie & Tennett	(Gasunie & Tennet, 2019)	Infrastructure Outlook 2050	2050	The Netherlands

The vision comparison and factor analysis result the in the following steps:

1. Identify key elements of report
2. Identify PESTLE indicators mentioned in compared visions
3. Provide quantitative summary of compared visions
4. Compare results
5. Provide factor analysis based on current system and vision comparison results

The system orientation, with especially the factor analysis (step 5 vision comparison), will provide the basis for the following stages to construct visions.

3.2 Stage 2: Vision construction

Stage 2 focuses on construction of a vision for hydrogen in the Netherlands for 2050. First a vision is selected by choosing the key components for the vision with a morphological chart (Ritchey, 2014). After vision selection the vision is further constructed. The following steps have been selected based on certain elements of literature from 2.3 Visions and Visioning and Ritchey (2014):

1. Define criteria of scoring
2. Identify extremes in visions
3. Define parameters system
4. Assign relevant conditions to parameters
5. Select conditions for each parameter for three visions based on low, medium and high integration of hydrogen in energy system
6. Check cross-consistency in constructed visions
7. Describe visions on:
    a. Narrative description of the hydrogen system.
    b. Technology deployment is expressed in quantitative indicators.
    c. System diagrams that represents the vision.
8. Verify visions with interviews

Extremes in visions are defined as the end values of scoring criteria and form the basis for three visions (Step 2). Thereafter the other visions are placed within this scope. Based on the extremes, components are selected and structured in a morphological chart (Step 3-6). A morphological chart will help to explore the different options as a result of the comparison of existing visions (Silvester, Beella, van Timmeren, Bauer, & van Dijk, 2013) and help to explore diverse solutions there are to reach climate change goals with hydrogen (Quist, 2016). After selection of components, it should be checked whether they are consistent. In case components lead to a conflict, a non-realistic vision is created. The selection of several components will provide the basis for vision construction.

The construction of a vision will have several components (Step 7). The visions are provided with a narrative description of the hydrogen system, the key elements and PESTLE aspects. Furthermore, quantitative indicators are given on share of technologies and technological development. Last a system diagram is provided for each system connecting the key elements for the desired outcome.

After construction of visions, the visions will be verified in interviews (Step 8). More on the interviews is described in 3.5 Interviews.

The visions provide the starting point for backcasting analysis, pathway analysis and roadmapping. All the following stages will allow to identify how the vision can be realised in the future.

3.3 Stage 3: Backcasting

Stage 3 formulates objectives for vision development over time by backcasting. As described in 2.4.1 Participatory backcasting after vision development the changes should be identified on what needs to change in order to reach the vision. In order to identify change WHAT-HOW-WHO questions are raised both preliminary as in interviews to validate the outcome. According the following steps the backcasting stage will be conducted (Jaco Quist, 2016):

1. Conduct preliminary analysis with desk research
    a. WHAT-HOW-WHO analysis part 1: WHAT are the (technological, cultural-behavioural, organizational and structural-institutional) changes?
    b. WHAT-HOW-WHO analysis part 2: required actions and stakeholders.
    c. Identify drivers and barriers
2. Conduct interviews with focus on:
    a. WHAT-HOW-WHO questions
    b. Identify drivers and barriers
3. Verify and adjust preliminary analysis based on outcome interviews.

Before interviews are conducted a preliminary analysis will be conducted where the WHAT-HOW-WHO questions are answered (Step 1). More detail on interviews is described in 3.5 Interviews. The outcome of the interviews will be analysed and compared to the preliminary analysis. The result of the backcasting analysis is an overview of changes with its related actions and stakeholders. Furthermore, the drivers and barriers for a certain vision are identified.

3.4 Stage 4 & 5: Pathway determination and Roadmapping

The first actions towards realising the visions are identified in stage three. For stage 4 it becomes important to place the actions in time and identify the pathway related to the vision. Stage 5 roadmapping provides insights in how to realize the visions and how to overcome the bottlenecks. For stage 4 and 5 the method is similar to stage 3 with preliminary definition of pathway/roadmap and interviews (3.5 Interviews).

Three steps of Foxon et al. (2010) are used with some adjustments of other literature for stage 4:

1. Place actions in time
2. Identify dynamic process
3. Specify interactions giving rise to or strongly influencing transition pathways
    a. Focus on the relation between vision, actors and technology (Hughes, 2013)
4. Specify bottlenecks that cause tension between vision and current system (Geels et al., 2018)

The actions that are identified in stage 3 need to be allocated to changes in the current system and at niche level (Step 2 pathway determination). The actions at niche level provide with the developments at niche level insights on dynamic process at this level. It can be determined how fast technologies need to emerge in order to realise the vision. To understand the role of actors, the influence of visions on actors and the changes in infrastructure need to be determined (Step 3 pathway determination). The step will allow to identify interactions between actions, actors and technological development.

As a starting point for stage 5 roadmapping, the bottlenecks need to be identified in order to find solutions how to overcome the bottlenecks in the transition pathway (Step 4 pathway determination. For technological, cultural-behavioural, organizational and structural-institutional change, strategies need to be determined such as collaborations, policy, organizational change, business case development etc.

Several steps are necessary to provide a roadmap to the future visions based on roadmap of the Noordelijke Innovation Board (2017):

1. Identify key phases of roadmap
2. Allocate phases in time related to actions in time structured to key elements
3. Define supporting measures to overcome bottlenecks
4. Identify responsible party to actions in time
5. Define dependencies of actions and actors in time
6. Determine costs related to the system in time

In order to locate actions to different phases, the phases should be described on what should be included for each vision (Step 1 roadmapping). The key elements as formulated in stage 1 form a basis for paths in the roadmap and actions should be aligned to the key elements in the different phases (Step 2 roadmapping). In order to overcome bottlenecks, strategies need to be formulated (Step 3 roadmapping). Actors should be assigned to actions to understand who is responsible for the end product and to provide insights what actors should collaborate in time

(Step 4 and 5 roadmapping). This will lead to a roadmap that shows dependencies of different actions and actors for the vision to succeed.

3.5 Interviews

Interviews are conducted to validate outcomes and to gather results in stages 2 till 5. Table 2 provides an overview what the aim is per stage for the interviews. Questions are asked within one session of an hour. Interviewees are selected based on the different aspects of the value chain to provide a clear overview of all the sides of hydrogen futures in the Netherlands after conducting a stakeholder analysis.

3.5.1 Interviewee selection

Two groups of interviewees are identified, i.e. experts and stakeholders. Experts are seen as researchers on the topic of hydrogen or energy systems. In some cases, they might also be involved in several hydrogen related projects, but this does not change the way they are interviewed for this research. Stakeholders are involved in the current system of hydrogen or may play a role in future hydrogen systems as identified in stakeholder analysis. Interviewees are contacted via TU Delft network, Accenture network and LinkedIn. A preliminary research took place for interviewees with asking supervisors, reading reports and reading news articles on hydrogen. Stakeholders are selected in such a way all identified topics are covered, i.e. production, distribution, power generation, built environment, transport and industry.

Table 2 - Overview topics interview question linked to stages

Stage 2	Verification of visions	- Positive feedback - Improvements
Stage 3	Backcasting analysis	- WHAT-HOW-WHO questions - Barriers and drivers
Stage 4	Pathway analysis	- How are the actions placed in time - What actions relate to current system - Interaction vision, actor and technology - Bottleneck
Stage 5	Roadmapping	- Dependency actions in time - Overcoming bottlenecks - Key actors with key actions

3.5.2 Interview format

Each interview starts with consent for taking part in the project in consensus with human research ethics for interviews. Interviewees were asked if their name could be used and if they were willing to take place in the project. The interviewees are involved in sector specific companies. Anonymized interview results could still be reduced to the interviewee, and thus are not provided.

The interview focusses on the elements as mentioned in Table 2. First questions on the interviewees relation to hydrogen is discussed. Second the constructed visions are presented. Often visions are described, and, in some cases, a short description is shown to the interviewee. Based on the constructed visions question on backcasting, pathways and roadmapping are asked.

The design thinking method a change journey is used as a backbone for the questions on backcasting, pathways and roadmapping. The change journey method is used as a backbone for the stakeholder interviews. The method focusses on the role of the stakeholder for a certain vision and how the role may change over time. The change journey method identifies the initiatives, measures of success, who will make the change happen, what will be impacted, what support is needed, and wat data is needed. The journey can be tracked through different phases of the stakeholder. The vision is discussed on a level of what benefits and challenges there are for the stakeholder. This will be a starting point for the actions the stakeholder needs to make, with whom and with what support. The actions are defined through the different phases of the roadmap and will allow to understand what the stakeholder needs in order to realise the vision. In some cases, the role of a certain stakeholder will be less of importance in visions. Stakeholders will be asked in what visions they see a role for themselves and to what extent.

At the end of each interview the interviewee is asked if they have final remarks.

3.5.3 Analysing interviews

With consent of interviewees, interviews are recorded. In some situation it is not possible to record the interview, instead notes are taken. The interview recordings are made in a transcript. The interview notes are described in an interview summary. Both interview summaries and transcripts are verified with the interviewees.

After taking the interviews and processing the results, the transcripts and interview summaries are coded. Coding exists of different phases. First elements based on Table 2 are highlighted/coded. Second, those coded elements are linked to vision 1, 2 and/or 3. Accordingly all coded elements are gathered per chapter. In the different chapters the elements are analysed, summarized and summed up to provide results for the three visions in backcasting, pathways and roadmaps. For coding, the interviews are printed and with colour coding analysed.

4 System orientation

The system orientation consists of description of current system, actor analysis, vision comparison and factor analysis. The system is described in section 4.1 Current system, 4.2 Potential markets future hydrogen system and 4.3 System diagram. The actor analysis is described in section 4.4 Actor analysis. The vision comparison is described in section 4.5 Vision analysis with the factor analysis in section 4.6 PESTLE analysis. Final, the chapter is concluded with section 4.7 Conclusion System Orientation.

4.1 Current system

In the current system, first, the role of hydrogen in the climate agreement and the demand for hydrogen is discussed. Second, different production for hydrogen are explained with finally the potential infrastructure for hydrogen.

As stated in the Climate Agreement, the Netherlands is setting the target for 2030 to reduce greenhouse gas emissions with 49% compared to 1990 with the aim to increase the EU target to 55% reduction (Rijksoverheid, 2019). For 2050 the target is set on 95 % reduction relative to 1990.

Furthermore the Climate agreement states, hydrogen is seen as a potential energy carrier to facilitate in reaching the climate change goals, for the long term of 2050 and beyond. There are iniatives for a hydrogen system to provide carbon free energy and offer alternatives for current feedstock. The Dutch government has identified five major functions for hydrogen in the near and further future (Rijksoverheid, 2019):

1. Carbon free feedstock for process industry
2. Carbon free energy carrier of high temperature heat in process industry
3. Energy storage and transport capacity to enable renewables
4. Transport
5. Built environment.

The government specifies the following targets involoving hydrogen in the Climate Agreement. First they aim to construct 800 MW of electrolysis capacity by 2025. Further development of the hydrogen market will go alongside the expected strong European hydrogen market. In 2030, it is aimed to reduce the CAPEX of electrolysis with 65% (from 100 million per 100 MW to 35 million) with a realized capacity of 3-4 GW. Since there is large potential in connecting hydrogen production to wind on sea, growth of hydrogen in the coastal area is expected.

The hydrogen market in Europe produces around 90 billion m3 hydrogen in 2007 (DNV GL, 2017b) and 80 billion m3 of European member states (Roads2Hy.com, 2007). In terms of energy, that refers to roughly 870 PJ/year in the EU.[1] The hydrogen demand counts for a share of 1% of the final energy consumption in the EU.[2] 50% of hydrogen is used for refinery and 32% for the production of ammonia. In contrast to the EU, the Netherlands has a large industry. The yearly production of hydrogen is around 10 billion m3 per year, equivalent to 96-110 PJ/year, what is nearly 13% of the total hydrogen demand in the EU. The hydrogen demand covers a share of roughly 3% of the Dutch final energy consumption, 3 times the EU share.

In the Netherlands, 80% of hydrogen is produced from steam methane reforming (SMR) of natural gas and 20% is a by-product of the chemical industry (Berenschot & TNO, 2017). Hydrogen is used for industrial applications with 60% for ammonia production and 40% in the (petro)chemical industry.

Due to the industrial application of hydrogen, hydrogen is connected to industrial clusters in the Netherlands. The largest industrial cluster is located around Rotterdam. For Rotterdam, an infrastructure is in place that connects France, Belgium and the Netherlands (CE Delft, 2018).

4.1.1 Production of hydrogen

Grey, blue and green hydrogen are considered as production methods for hydrogen in the Netherlands. Each method is explained briefly based on Acar & Dincer (2014).

Grey hydrogen is produced in a process called steam reforming (SMR). Natural gas is the source for the process. Hydrogen and carbon monoxide are generated. From the carbon monoxide in a combination with water, hydrogen and carbon dioxide are produced. Efficiency for the process lies around 76% (IEA, 2019). Benefits of natural gas steam reforming are the viability, low costs and existing infrastructure. Challenges are the capital, operation and maintenance costs. On the other side, the process exists of carbon emissions which should be reduced to reach climate goals.

A solution to capture the carbon is blue hydrogen. The process combines natural gas steam reforming with carbon capture storage (CCS)(CE Delft, 2018). During the process, carbon is

[1] 1 billion m3 hydrogen is equal to roughly 10,9 PJ hydrogen. (Avebe et al., 2019)

[2] Final energy consumption EU and NL from Eurostat (2015).

captured and transported to a CCS location. Blue hydrogen is seen as a transition technology until hydrogen can be produced without emissions.

A method without natural gas is green hydrogen production. For green hydrogen, renewable energy sources are connected to an electrolyser that generates hydrogen from water and electricity. A by-product in the process is oxygen. Green hydrogen production has no carbon emission from natural gas. The produced hydrogen can be used again to generate electricity in hydrogen fired power plants or in fuel cells. The largest advantage of green hydrogen is the low level of pollution when connected to renewable sources. Challenges are efficiency losses with power to gas to power, high capital costs, competitive position in comparison to natural gas steam reforming, integration with renewable energy sources.

4.1.2 Infrastructure

Currently the infrastructure for hydrogen in the Netherlands is based on the industry demand in industrial areas. The infrastructure exists of pipelines in the Port of Rotterdam going to Belgium. The infrastructure is a private system, meaning that the owner of the infrastructure decides who is included in the infrastructure and who is excluded. Two companies active in operating the infrastructure are Air Liquide and Air Products[3]. Both companies have their own private infrastructure as shown in Figure 9.

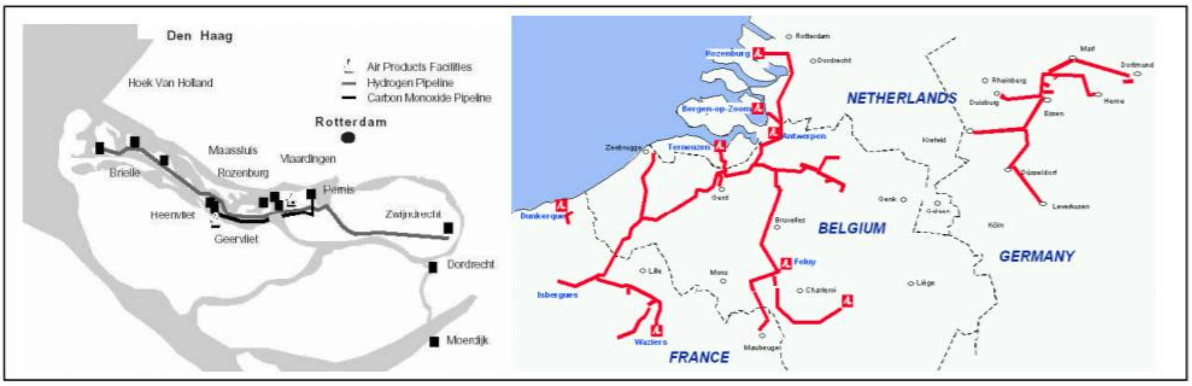

Figure 9 - Existing infrastructure hydrogen of Air Products (left) and Air Liquide (right) (DNV GL, 2017b)

The potential of the natural gas infrastructure for transportation of hydrogen is often mentioned in literature both for a mixture of hydrogen with natural gas as for a full hydrogen infrastructure. From a technical point of view it is possible to adjust the existing natural gas infrastructure to

[3] Air Products and Air Liquide are companies that provide gasses and chemical products for industry. Air Products operates a pipeline system of roughly 140 km in the Rotterdam region. Air Liquide operates a pipeline system between France, Belgium and the Netherlands of 1000km which is the largest in Europe. (DNV GL, 2017b)

a full hydrogen system or to a natural gas and hydrogen mixture (DNV GL, 2017b). Some technical specifications on safety and the behaviour of pipelines needs further attention.

Currently the hydrogen infrastructure is privately operated. For hydrogen to be operated in the natural gas transmission and distribution grid by TSO and DSOs, the Gaswet needs to be adjusted. The Gaswet in the Netherlands states that a mixture of mainly methane can be transported through the gas infrastructure, what means hydrogen cannot be transported in the current natural gas infrastructure (Gasunie, n.d.).

Furthermore, grid operators have delivery obligations. Natural gas is seen as a utility and should be available on demand. In case hydrogen becomes a utility and the grid becomes publicly operated, challenges for grid operators could occur with delivery obligations.

In a future energy system other means of transport could be used besides pipelines for hydrogen. Hydrogen could also be transported by trucks and boats for long distance transport. Depending on the daily need and transportation distance, different means of transport are best (DNV GL, 2018). What the future hydrogen infrastructure will look like depends on the market development and demand for hydrogen in the future. Decisions should be made on a central or decentral infrastructure with what means of transport.

4.2 Potential markets future hydrogen system

This section describers the potential markets for hydrogen by 2050. First the industry is discussed in more detail, followed by transport, built environment, and storage and electricity generation.

The Hydrogen Council (2017) highlights that hydrogen enables the renewable energy system and decarbonizes end uses (Figure 10). Renewable energy systems are enabled by hydrogen through integrating large-scale renewables, distribution of the generated energy across long distances and potential for storage. There is a potential for decarbonization of end use are in transportation, industry, built environment and feedstock. The Hydrogen Council hydrogen potential complies with the five functions as formulated by Klimaatberaad (2018) as mentioned in 4 Current system.

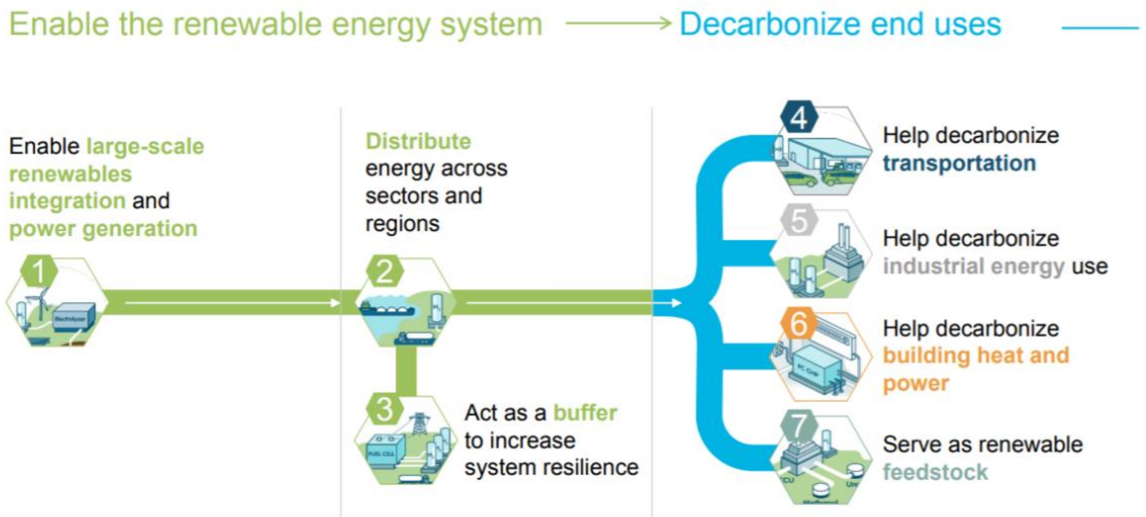

Figure 10 - The different roles of hydrogen in the energy transition according to the Hydrogen Council (2017).

How the different functions or markets will develop is highly uncertain and depends on many indicators.

4.2.1 Industry

The current demand for hydrogen in industry is 96-110 PJ/year. Hydrogen is produced as feedstock in refining and for production of ammonia (DNV GL, 2017a; Le Duigou et al., 2013). To decarbonize the production of hydrogen CCS should be added to existing SMR or production should be replaced by electrolysis.

Furthermore, hydrogen could offer a solution for high temperature heat in industry (DNV GL, 2018; Ruhnau et al., 2019; Sgobbi et al., 2016). Heat covers 415 PJ in 2017 of final energy usage of which mainly the heat is provided of natural gas and oil (EBN, 2018b). Figure 11 shows demand for heat in 2013 with expected developments for 2030 and 2050. The reductions are expected to take place due to efficiency measures and other technological developments. Over a 100 $_{o}$C can be seen as high temperature. The quality of hydrogen in heating applications can be less than for feedstock purposes, because in burning processes by-products will not disturb the process. Development

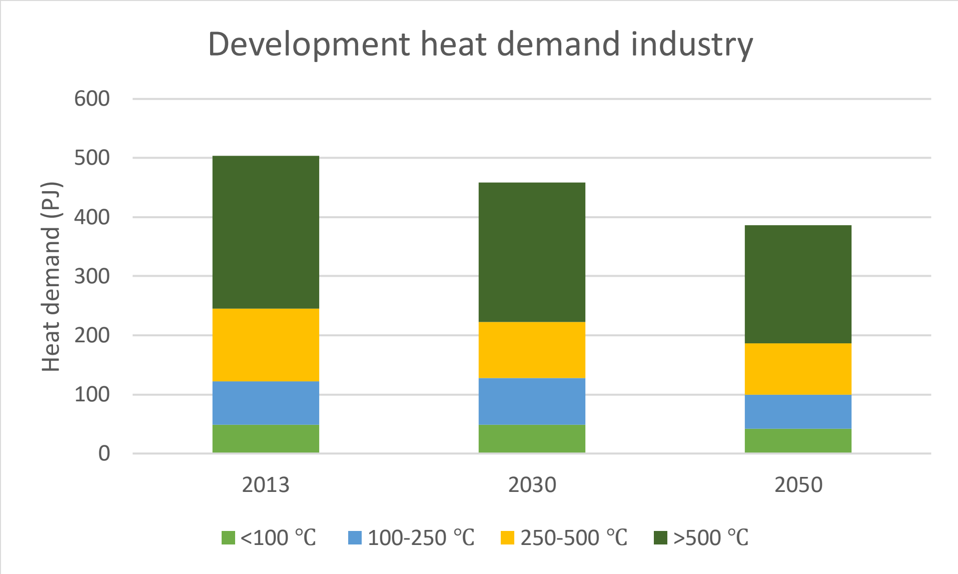

Figure 11 - Heat demand for industry with expectations for 2030 and 2050. Sources: (BlueTerra, 2018; CE Delft, 2015)

When considering a bio based circular industry, hydrogen can play an important role in linking hydrogen with captured carbon to make new products. This process especially benefits using green hydrogen.

4.2.2 Transport

Often hydrogen is named to replace fossil fuels in transport. Currently most vehicles are based on diesel and gasoline. Slowly EV are increasing and emerging in passenger transport.

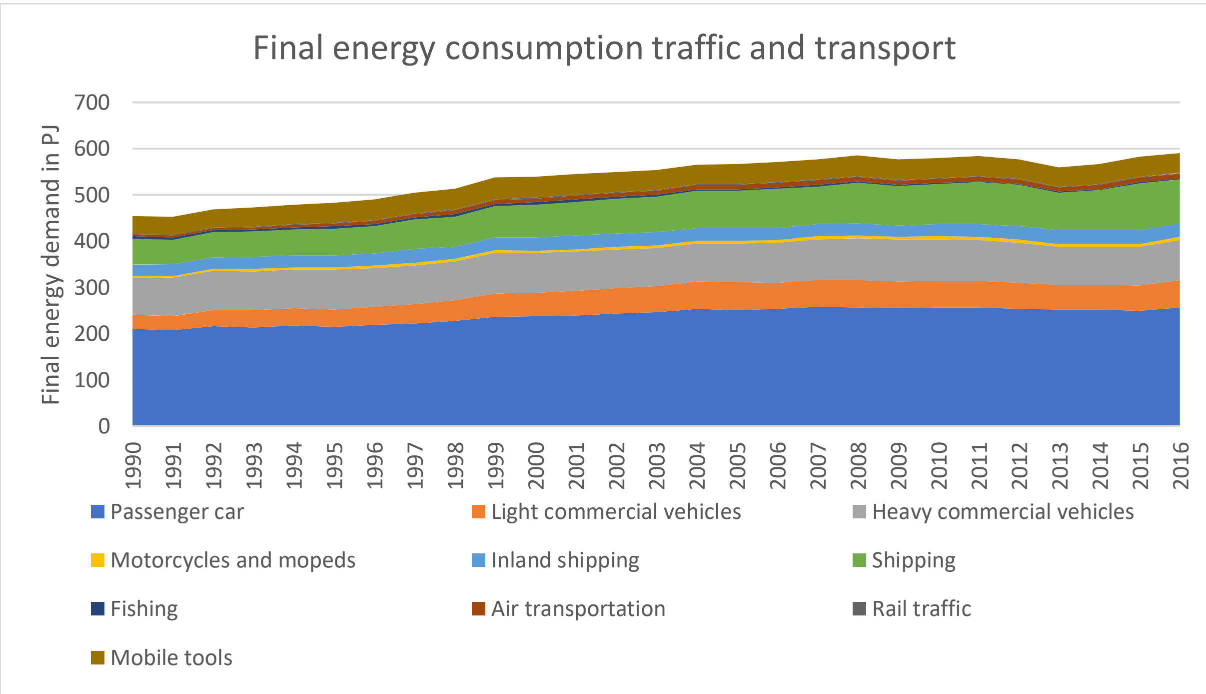

Figure 12 - Final energy demand traffic and transport between 1990-2016. (CBS, PBL, RIVM, & WUR, 2018)

Hydrogen can especially play a role for long distance passenger transport, heavy vehicles and shipping (Thomas, 2009). Figure 12 shows the final energy consumption traffic and transport over the years. All the transport modes offer opportunities for hydrogen. In passenger transport, electric vehicles will play an important role, especially for short distance travel. Long distance travel often is done in the current system with diesel fuelled cars which can be replaced by hydrogen cars (Figure 13). By 2050, the final energy consumption in transport will decline as described by the European Commission (2018). Overall final energy consumption of transport is expected to decline between 10-50% by 2050 dependent on the scenario.

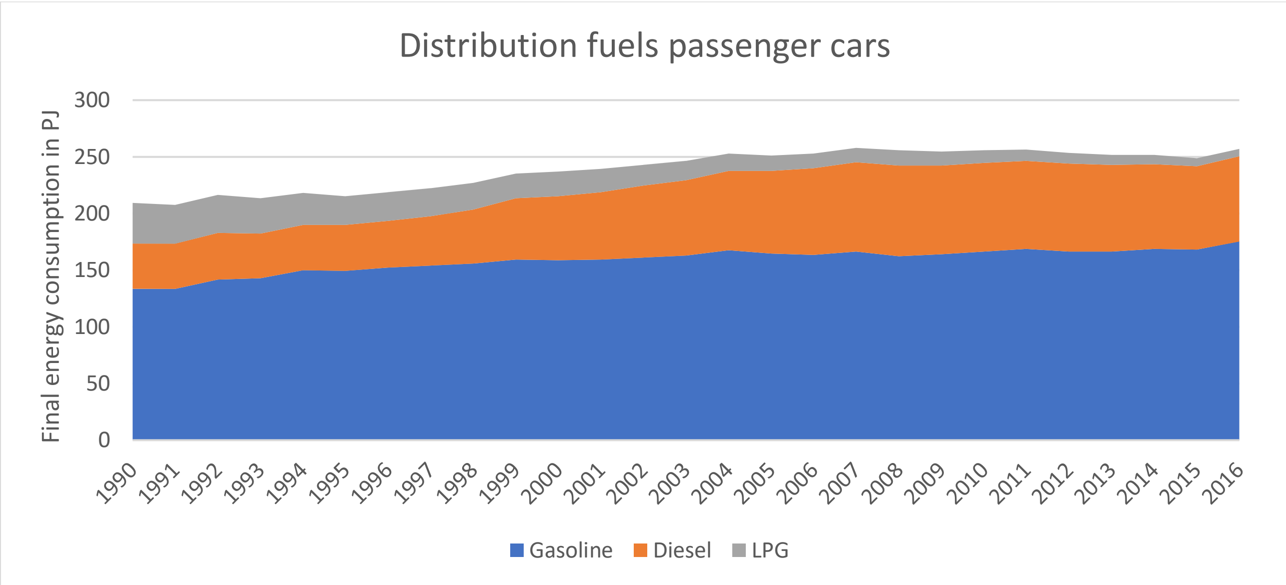

Figure 13 - Distribution fuels for passenger cars between 1990-2016. (CBS et al., 2018)

4.2.3 Built environment

Built environment covers utility and households in the Netherlands. Roughly 70% of the final energy demand in built environment is used for heating (EBN, 2018a). Natural gas covers the largest share of fuel for heating with around 85%.

In the Dutch government aims to reduce natural gas use in built environment to reduce extraction of natural gas in Groningen and to reduce carbon emissions with 3,4 Mton in the built environment (ECN, 2017; Rijksoverheid, 2019). The final energy demand for heating is expected to decline due to efficiency measures (Figure 14). Heating systems that show potential are districted heating, electric heat pumps and green gas (ECN, 2017). Hydrogen is in many studies not mentioned as an alternative for heating, because the technology is expensive and not yet market ready. However, hydrogen could offer a solution for households in less insulated urban areas where district heating is not an option and electric heat pumps will need a large amount of electricity to heat a building at peak demand (DNV GL, 2018; Sgobbi et al., 2016; Wijk & Hellinga, 2018). Hydrogen can be stored over long time periods and therefore provide a better solution at peak demand. With scale the overall costs for hydrogen in built environment will go down.

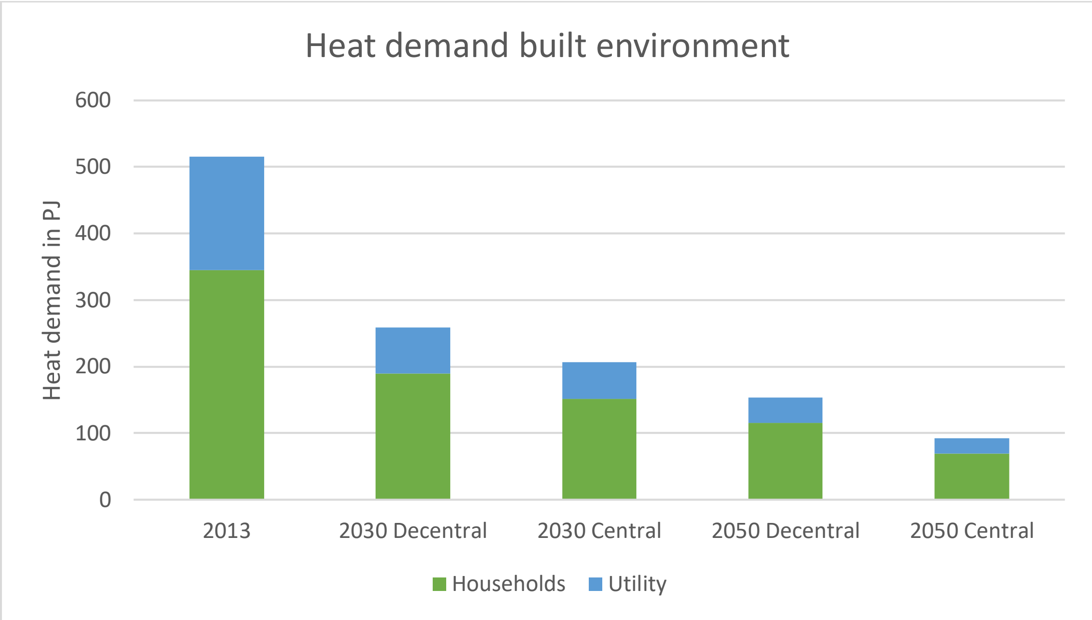

Figure 14 - Development of heat demand for 2030 and 2050 in utility and households in different scenarios. Both scenarios are designed to reach the 2-degree target. Scenario central has a focus on central energy generation with CCS, biomass and distributed heat. Scenario decentral has a focus on decentral energy generation with strong energy efficiency measures, electrification, less fossil fuels, and other renewable sources. (CPB & PBL, 2016)

4.2.4 Storage and electricity generation

Hydrogen has potential in energy storage and electricity production. The current electricity production comes mainly from natural gas, coal and renewables (Figure 15). Hydrogen can be used in flexible gas-fired power plants as fuel (Breeze, 2017; DNV GL, 2018). This process is only efficient when hydrogen is produced from electrolysis or is imported, since SMR uses natural gas, what can be used in gas fired power plants too.

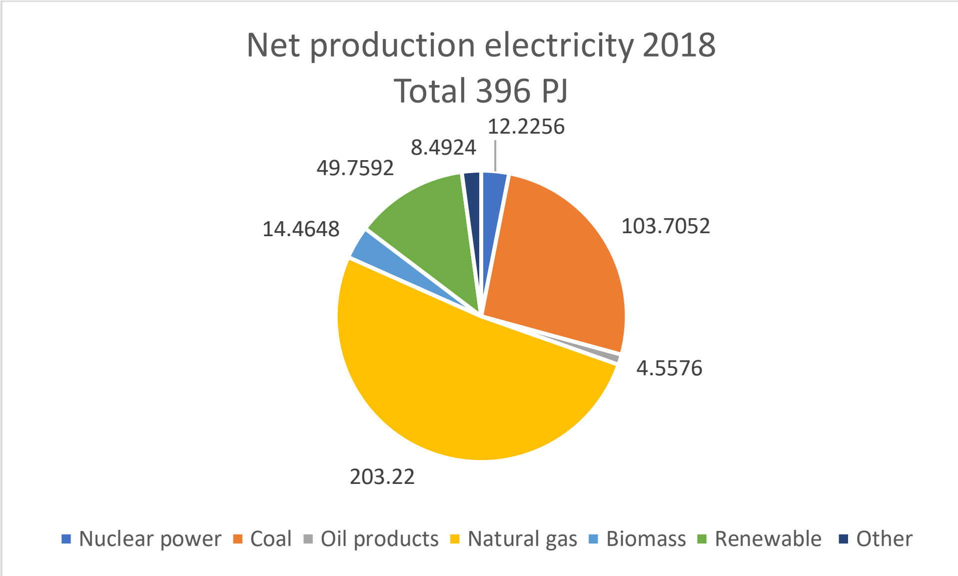

Figure 15 - Net production of electricity in 2018. (CBS StatLine, 2019)

Hydrogen has potential for flexibility of the power grid and electricity demand, in case the production is not used for other applications than power storage. Hydrogen is often linked to offshore wind in order to solve issues with seasonal fluctuations, transport and overproduction. With current offshore wind projects the total capacity in 2030 will be around 11 GW (Rijksoverheid, n.d.). Growth of offshore wind is estimated to be 0,88 GW per year between 2019 and 2030. Between 2026 and 2030 the expansion is around 1 GW per year. In the climate agreement a maximum capacity of 60 GW is mentioned for offshore wind (Rijksoverheid, 2019). TKI Wind op Zee (2019) predicts a capacity between 35 to 75 GW in 2050. The necessary installed capacity will vary in different scenarios, especially when direct interconnection between offshore wind and electrolysis is considered. In a system where hydrogen is used as storage facility for energy and electricity demand, the overcapacity will be transformed in hydrogen and later used for electricity production.

4.3 System diagram

The different applications for production, transport and end-use are shown in Figure 16. The blocks with filled lines represent the existing system. Hydrogen is currently produced from natural gas in SMR. Hydrogen is transported to the end user by pipeline infrastructure and used in industry as a feedstock fuel. Alternatives for production is the inclusion of CCS in the grey hydrogen production chain or electrolysis from electricity (preferably RES). Furthermore, potential markets are transport, high temperature industry, built environment and power balance.

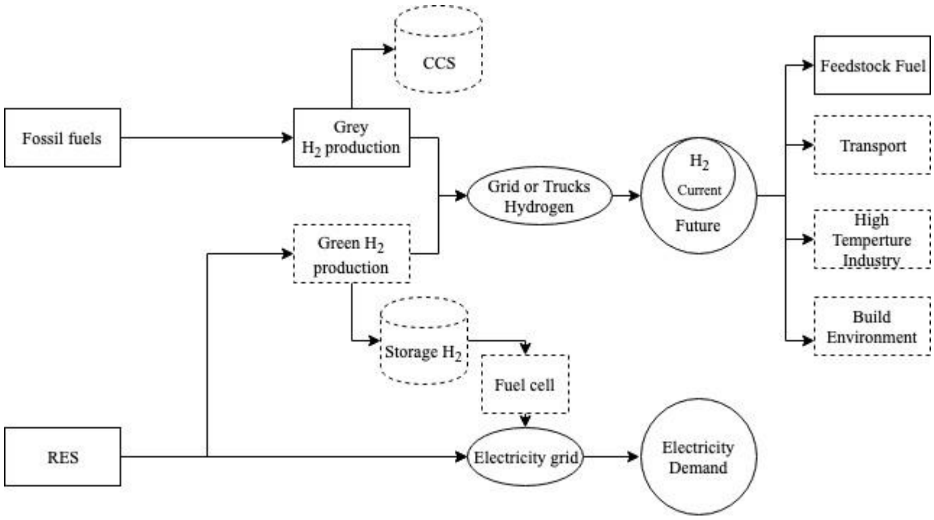

Figure 16 - hydrogen system diagram

4.4 Actor analysis

Industrial actors are involved in the current hydrogen system from supply to end-use for different purposes. With emerging applications for hydrogen, new actors become involved. The data for the actor analysis is based on preliminary literature research and further elaborated in the interviews with stakeholders and experts. In this section, actors are briefly discussed on mutual relations and their position with the changing system. First actors in the current system are discussed, followed by general actors in the potential hydrogen system, actors in transport, actors in built environment, actors in electricity, actors in industry and actors in production.

4.4.1 Current system

Hydrogen in the current system is used in refinery, ammonia industry. Table 3 provides an overview of the actors in the current system of hydrogen in the Netherlands. Hydrogen is produced by specialized chemical companies that own grey hydrogen plants and infrastructure to deliver hydrogen at customers. In the Netherlands, Air Liquide and Air Products have the largest hydrogen production capacity and infrastructure. Often refineries and other users of hydrogen have backup capacity for hydrogen production via grey hydrogen and produce hydrogen at their operation. Hydrogen is also produced as a by-product in chemical industry, where it is sold to hydrogen distributers. An increasing demand for hydrogen in the system challenges hydrogen distributers to match the demand in case more customers are connected to the grid. A challenge with green hydrogen production is whether the supply of electricity will be stable to fulfill a constant production of hydrogen. Existing end users of hydrogen require a stable supply of hydrogen. In case the producer and distributer cannot fulfill the demand, end users will either find another supplier or extend their own hydrogen production capacity.

Table 3 - Actors current system

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
(Petro) Chemical companies	End user and producer	Potential producer of hydrogen via electrolysis	Buy cheap hydrogen with secure flow of supply	Production of hydrogen not relevant; cost effective prices
Ammonia Industry	End user and producer	Keep low cost hydrogen with security of supply.	Buy cheap hydrogen with secure flow of supply	Production of hydrogen not relevant; cost effective prices
Hydrogen Suppliers (Air Products & Air Liquide)	Producer and grid operator	Potential increase of demand hydrogen.	Provide cheap, supply secure and quality hydrogen to clients.	With increasing hydrogen and changing rules, role of hydrogen supplier may change overtime.

4.4.2 General actors potential hydrogen system

Some actors are not currently active in the hydrogen system, but with new applications emerging they will play a role in every potential market. An overview of the general actors for potential hydrogen system are shown in Table 4.

Governmental bodies strongly influence the realization of hydrogen. With clear regulations and policy, investment risks are taken away. For hydrogen to become competitive, subsidies are necessary to compete with alternatives. The government has the largest influence on the direction and vision for hydrogen. The Ministry of Economic Affairs and Climate is the executer of supporting regulations and policy.

Further research and development are needed for hydrogen applications. Knowledge institutes and universities play an important role in proofing, scaling and optimizing hydrogen technologies. Furthermore, they consult on different system configurations where hydrogen is involved.

Distributed System Operators (DSO) and Transmission System Operators (TSO) are very important actors in the energy transition and therefore also for hydrogen. To what extend they will play a role in the future of hydrogen depends on the scale and the regulatory framework designed by the government. While Tennet is looking for alternative energy carriers, Gasunie is seeking an alternative purpose for their natural gas grid. DSOs are facing reductions of natural gas and the upcoming of alternatives. In every potential market, DSOs and TSOs may play a role in the distribution of hydrogen, while this is subordinate to the development of the different potential markets. In each potential market, new players may become responsible for a part of the infrastructure.

Table 4 - General actors potential hydrogen system

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
Tennet	TSO electricity	Hydrogen infrastructure may offer a solution to lower electricity grid capacity.	Provide stable infrastructure of electricity with third party access.	Actions limited by law. Need alternatives to stabilize increase of electrical capacity.
Gasunie	TSO natural gas	Find alternative for natural gas in existing infrastructure. Unburden grid capacity TSO electricity.	Provide stable infrastructure of gasses with third party access.	Actions limited by law. Can offer support to stabilize increase of electric capacity. Hydrogen might be optional alternative natural gas.
DSO (e.g. Liander, Enexis, Stedin)	Grid operator electricity & natural gas	Decarbonize built environment. Optimize distribution electricity grid.	Provide stable supply of gas on demand.	Off the gas: alternative for heating and alternative for existing grid. Actions limited by law
Ministry of Economic affairs and climate	Public institution	Decarbonize industry, transport, power and building sector	Have a sustainable system by 2050 with 80% GHG emissions.	Industry should take lead in how to integrate hydrogen and file for subsidies etc. Time will tell on institutional change
Knowledge institutes	Research	Provide knowledge on hydrogen	Realize optimal energy system with certain level of hydrogen.	Show what the best solution with hydrogen and for the energy system is.

Universities	Research	Provide knowledge on hydrogen	Realize optimal energy system with certain level of hydrogen.	Show what the best solution with hydrogen and for the energy system is.

4.4.3 Potential market: transport

The system analysis showed the potential for hydrogen in the transport sector. Hydrogen offers especially a solution for heavy vehicles, ships and long-distance transport. When hydrogen becomes incorporated in the transport sector actors involved in the supply chain of transport will become part of the hydrogen actor system (Table 5). Car manufacturers design hydrogen cars with either fuel cell technology or a combustion motor on hydrogen. Hydrogen cars need to be scaled-up to create a cost-efficient market. The same applies to shipyards and heavy vehicle manufacturers (e.g. trucks and busses). For manufacturers there must be a driver for hydrogen in order to make the technology cost efficient. An infrastructure of refueling stations for hydrogen should be designed and implemented in the Netherlands in order to allow a market for hydrogen vehicles. Several parties could play a role in hydrogen refueling stations, namely existing refueling station operators or new parties. In case of a central hydrogen infrastructure, the operator of the hydrogen infrastructure could become involved in the refueling infrastructure. In addition, car resellers and drivers should be willing to buy, drive and use hydrogen vehicles. Hydrogen vehicles enable long distance travel, while electric vehicles have limited driving distance on one tank[4]. Commercial transport companies and shipping companies are looking for cost efficient transport means. Hydrogen needs to become competitive and the infrastructure needs to become efficient to replace fossil fuel driven transport means. Hydrogen transport may get a boost when stricter regulations on emissions are implemented for transport and shipping companies.

Demand for hydrogen vehicles, hydrogen refueling infrastructure and availability of hydrogen vehicles for simultaneous development. The chicken and egg problem can be noted because realization of hydrogen in transport strongly depends on the development of demand, infrastructure and availability. Good communication between the actors will lead to less investment risk and security of supply chain development.

[4] In case of an electric vehicle the “tank” is a battery.

Table 5 - Transport specific actors hydrogen system

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
Transport companies	End user hydrogen as fuel	Decarbonize ways of transport.	Cost effective and clean transport with emphasis on cost effective.	Electricity not the option to decarbonize entire transport sector. Other alternatives are necessary.
Shipping companies	End user hydrogen as fuel	Decarbonize ways of transport.	Cost effective and clean transport with emphasis on cost effective.	Electricity not the option to decarbonize entire transport sector. Other alternatives are necessary.
Shipyards	Production hydrogen ships	Construct ships that match the demand.	Competitive advantage for first movers on hydrogen shipping market.	Hydrogen as fuel for ships is highly uncertain. Shipyards are hesitant for risks of market development.
Car manufacturers	Production hydrogen vehicles	Produce alternative vehicles to decarbonize transport sector.	Create competitive advantage with early development of hydrogen vehicles.	Scale of production hydrogen vehicles depends on markets. Produce vehicles for leading hydrogen regions.
Gas stations (e.g. Shell, BP, Texaco)	Operate refuelling infrastructure	Operate a cost-efficient refueling infrastructure to match demand.	When demand for hydrogen as fuel increases, offer accessible hydrogen. Early market entry may lead to extensive market share.	First mover advantage may lead to market share, while large uncertainty is related to potential market development and cost-efficiency.
Specialized refuelling companies	Operate refuelling infrastructure	Operate a hydrogen refueling infrastructure for hydrogen vehicles	Facilitate hydrogen refueling stations to enable hydrogen vehicles. Early market share may offer opportunities for larger hydrogen market.	Refueling infrastructure is necessary to enable hydrogen transport. Small scale reduces risks.

Car owners	End user fuel	Affordable, clean and safe cars.	For long distance, hydrogen may offer a clean solution. Costs are a drawback.	Competitiveness of hydrogen to other fuels is key to create hydrogen market.
Car resellers	Reseller	Sell as much cars possible. Preferably with carbon free future in mind.	First mover advantage in expertise on hydrogen vehicles to gain market share.	Competitiveness of hydrogen to other fuels is key to create hydrogen market. Risks related to market.

4.4.4 Potential market: built environment

Currently in the built environment natural gas is used for heating. Driver for alternative heating sources are the earthquakes in Groningen and finding carbon free alternatives for natural gas. Various stakeholders are identified for specifically the built environment (Table 6).

DSOs (e.g. Liander, Enexis & Stedin), municipalities and regional authorities are looking for the best alternatives for natural gas. Hydrogen is considered as a solution in specific situation, i.e. old, poorly isolated buildings in urban areas. The role of the DSO is to find the best cost-effective solution. To facilitate a transition to hydrogen in built environment, a close collaboration with residents, housing corporations and home owners is needed. Owners have to accept a hydrogen heating system in their houses. A challenge is to overcome the price difference between natural gas and hydrogen. Scale in the built environment is needed to bring the prices down.

Scale is reached in collaboration with boiler manufacturers. Manufacturers will design hydrogen boilers. Scale and demand are a necessity for hydrogen boilers to be competitive and for manufacturers to produce boilers. Potential small markets can lead to high costs for both hydrogen boilers and hydrogen infrastructure in built environment. That may result in resistance of residents, home owners and housing corporations. Social acceptance of hydrogen in built environment is crucial for its succeeding. Costs and safety are strong indicators for social acceptance. The role of Autoriteit Consument & Markt (ACM) and DSO is to prove and guarantee safety of hydrogen in built environment.

Table 6 - Built environment specific actors hydrogen system

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
Boiler manufacturer (Bekaert heating & Remeha)	Manufacturer of hydrogen boiler	Produce alternative boilers to decarbonize built environment.	First mover advantages	Risk in market development and scale.
Housing corporations & home owners	Owners of buildings	Find best alternative for natural gas	Get the cheapest heating system that will be a long-term investment.	Hydrogen implementation is rather easy but comes with high costs.
Residents	Social group	Safe and cheap heating system.	Lowest costs for energy bill based on the heating system to have an alternative for natural gas. Safe heating system.	Social acceptability & easy implementation
Municipalities	Public Institution	Decarbonize region	Create decarbonization plans with best sustainable options.	Households need to go of the gas. Offer citizens guidance in decarbonizing household in cost-effective way.
Regional authorities	Public institutions	Decarbonize region	Create decarbonization plans with best sustainable options in Regionale Energy Strategie	In regions, buildings and industry need to decarbonize without high costs and losing industry.
ACM	Independent institution	Guarantee a safe and cost-efficient supply of energy (hydrogen)	Judge whether hydrogen is safe to use in built environment, transport and industry. Check monopolists on cost efficiency.	Hydrogen is new in some sectors. Good collaboration with stakeholders necessary for allowance of implementation hydrogen in sectors.

4.4.5 Potential market: electricity

Several actors are involved in the electricity sector. Sector specific actors are shown in Table 7.

Gasunie and Tennet are faced with challenges in their infrastructures. The increasing demand for electricity puts the electricity grid under pressure. Hydrogen offers a solution for the transmission grid operators to resolve challenges regarding energy distribution and storage. In case problems occur in the electricity grid, Tennet will contact utilities to solve the issue. A potential solution could be close collaboration with Tennet and Gasunie. Rules for TSOs may change over time, and therefore Gasunie could in future scenarios be allowed to operate electrolysis capacity. Gasunie can then transform electricity in hydrogen followed by storage for balancing needs or distribute hydrogen to end-users. Offshore wind operators will have overproduction of electricity in future scenarios. They can either collaborate with direct end use of hydrogen industry or transform the electricity to hydrogen in case of a surplus. Utilities have the same options as offshore wind operators (often also involved in offshore wind projects) or they can generate electricity with hydrogen fired power plants. With changing institutions, hydrogen may become interesting than other fossil fuel power plants.

Table 7 - Electricity sector specific actors for hydrogen system

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
Utilities	Producer and/or end user	Looking for alternative energy carriers, sources and new business cases for security of supply.	Cover peak demand with RES challenging, need for storage. Expanding electricity grid capacity is expensive and inefficient in terms of losses.	Hydrogen could offer solutions as alternative energy source and enables RES.
Offshore wind operators	Input for production	Use surplus offshore wind efficient. Create new business cases.	Use surplus offshore to store power in hydrogen. Connection of offshore wind directly to hydrogen production may offer opportunities.	Hydrogen is a stable energy carrier. Clean production of hydrogen via electrolysis needs a clean source like offshore wind.

4.4.6 Potential market: industry

While hydrogen is already used in industry as a feedstock, potential other applications in industry arise with new actors. Industrial clusters will play a crucial role in the role-out of hydrogen for industry. Industrial clusters facilitate collaborations and are aiming to create energy efficient industry. The Port of Rotterdam is a good example of an industrial cluster that is putting emphasis on decarbonization and sustainability. Hydrogen can be used for high temperature heating and to capture carbon into making new products. Especially chemical companies can play an important role in carbon capture and utilization with green hydrogen. For high temperature heating purpose, industry with high temperature will start using hydrogen when available and cost-effective. Heat providers and grid operators have to collaborate in order to facilitate high temperature hydrogen heat for industry.

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
Industry with high temp demand	End user	Looking for alternative for natural gas heating to decarbonize industry	Have cost effective industry. High standards, option to go abroad.	Demand: competitive costs hydrogen to natural gas, infrastructure, low transformation costs, security of supply hydrogen.
Ports & Industrial clusters	Management industrial regions	Looking for solution to decarbonize indusrial regions	Enable a bio based circular system in industrial region	Collaboration between industry and actors in industrial clusters can facilitate realizing the goals.

4.4.7 Production

While production of hydrogen is currently done via SMR, to match climate targets carbon capture and electrolysis should become more substantial. Air Liquide and Air Products are involved in production for commercial means and in the future their capacity might be extended with carbon capture applications.

Electrolysis is a known technology. Several manufacture electrolysis devices on small scale. The scale is expected to become larger, what means manufacturers of electrolysis should be able to scale and more companies can emerge.

Besides Air Liquide and Air Products, also other companies could become involved on the hydrogen market as producers. Chemical companies see an opportunity for hydrogen in circular economy to create new products and to optimize chains. Hydrogen opens new opportunities for companies as Nouryon and others.

Actor	**Function**	**Interests**	**Objectives**	**Problem perception**
Electrolysis manufacturers	Manufacturers of electrolysis	New interest for electrolysis offers opportunity.	Scale up with demand for electrolysis offers growing opportunities.	Green hydrogen offers many opportunities to grow. Challenge to scale up electrolysis manufacturing supply chain.

4.5 Vision analysis

Table 1 provides an overview of the visions that are compared for this study. Each vision has been analysed and compared based on PESTLE elements. A quantitative summary has been conducted provided, covering percentages of final energy demand and share in different sectors. The PESTLE analysis for each vision can be found in Appendix IV – PESTLEs vision comparison. All selected visions for vision comparison are briefly described as shown in Table 1.

4.5.1.1 Platform Nieuw Gas

In 2006 Platform Nieuw Gas published a report on hydrogen fuel for the transition. In the energy transition four issues were highlighted, namely, (1) energy security, (2) climate change, (3) environment/air quality, and (4) innovation and industry for Dutch industry. The main vision argues hydrogen can play a key role in solving the four issues. Energy security can be solved by the fact that hydrogen can be produced of every primary energy source. Hydrogen can reduce GHG emissions, reducing climate change effects. Hydrogen as an alternative for polluting fuels can solve the air quality problem. Although no clear pathways are discussed, the report differentiates between the different options in the value chain of hydrogen, the energy source, transport and storage, and application. Mobile and stationary applications are explored. For transport and distribution, a local infrastructure is compares with a national infrastructure. Production of hydrogen considers grey, blue and in time green hydrogen production.

In their vision, Platform Nieuw Gas argues that the pathway for a hydrogen future will start with transition activities in certain development areas with large hydrogen potential. Especially in the field of mobile applications, the effects will be largest regarding the four highlighted issues. Mobile application pathways integrate hydrogen in mobile solutions starting with public transport in cities to private transport. By 2050 Platform Nieuw Gas predicts 40-75% of transport is on hydrogen. By adding CCS, the production of hydrogen will be less emitting than the fossil fuel alternatives for transport. Stationary applications are predicted to reach a penetration of 10-30% by 2050. Stationary application use CHP systems in the built environment. The CHP systems will in the beginning still use natural gas, with a later shift to hydrogen. In the future, natural gas might be replaced by hydrogen in the current infrastructure. In new residential areas that assumption should be taken in consideration.

The report lacks data of hydrogen in the future energy system, though percentages in mobile and stationary applications are given. The report highlights PESTLE elements clearly. From the analysis it can be concluded the government should stimulate and structure Dutch hydrogen activities. Food guidance can lead to growth of hydrogen industry with many opportunities, participation and education are key, focus on technological front should be on commercialization of technologies, new market designs with adjusted law and regulations will enable hydrogen and hydrogen is an enabler of reaching climate targets.

4.5.1.2 Hisschemöller

From a study of Hisschemöller et al. (2007) three visions have been created with a working group assigned to each vision, i.e. (1) hydrogen in the current infrastructure, (2) hydrogen in transport and (3) decentral renewable in built. Pathways have been explored for the different visions and the benefits and constraints have been analysed by the working groups. As a result of the study five key institutional factors were identified that shape the further development of hydrogen in the Netherlands, namely (1) physical infrastructure, (2) centralized versus decentralized system, (3) the dominant knowledge system, (4) policy approach, and (5) lack of knowledge competition (Hisschemöller & Bode, 2011).

The first vision, hydrogen in the current infrastructure, explores the possibility of blending hydrogen with natural gas in the current infrastructure. The analysis highlights, gas and electricity become integrated, since hydrogen is seen as a storage medium for surplus energy. Using the current infrastructure burdens society less and while the technology has to be further developed for mixing. Issues that may arise are safety, leakage of hydrogen and technical difficulties. Other applications of hydrogen would make a bigger difference. Economical elements are lacking in the vision.

The second visions, hydrogen in transport describes, three pathways for clean transport i.e. biofuels in combustion engines, hydrogen in combustion engines and FCEV. The analysis emphasises that the government should take leadership in choosing a clean application for transport and stimulate clean transport. The discussion is raised whether biofuels can be categorized as a clean fuel. Thus, hydrogen FCEVs should be seen as the cleanest option. As critique on the vision, it is mentioned hydrogen is as clean as its production method. Furthermore, the commercialization of fuel cell vehicles is questioned. The Netherlands as a small country has little influence on the developments of hydrogen vehicles in the future of transport. The discussion of social elements is lacking in the vision.

The third visions, decentral renewable in built, describes two pathways; one with hydrogen and one without hydrogen. The decentral example with hydrogen entails a small initiative where households have the ambition to become self-sustaining. The surplus of electricity is converted to hydrogen via electrolysis. The hydrogen is thereafter used in a small CHP unit. The analysis highlights decentral local systems should be stimulated and facilitated. Economic and technical elements need further development for the vision to become cost efficient and technological feasible. More efficient applications such as hydrogen in transport sector is given as critique on hydrogen in decentral renewable application.

4.5.1.3 PBL

PBL (2011) has explored routes to a clean economy by 2050. The visions are based on GHG emissions reduction on four components: (1) reduction of energy demand, (2) use of biomass, (3) Carbon Capture and Storage (CCS), and (4) electricity generation with carbon emissions. The aim of the paper is to reduce GHG emissions with 80% by 2050 compared to 1990. In this report hydrogen is combined with electricity solutions. Social and legal elements are not mentioned in the report. Large potential for hydrogen is seen in transport with combustion engine on hydrogen and fuel cells for both passenger transport as for heavy vehicles. Smaller potential is seen in new residential buildings and utility buildings with micro CHP on hydrogen. Furthermore, in industry CHP can potentially run on hydrogen. For storage, not hydrogen, but methane gas is seen as a solution with as a in between step hydrogen. PBL mentions hydrogen electrolysis, SMR with CCS on natural gas and biomass gasification for production. Hydrogen application need further development. Governmental support of emission free vehicles might facilitate further development fuel cell vehicles.

4.5.1.4 Noordelijke Innovation Board

The Noordelijke Innovation Board (2017) has designed a detailed project for the Northern Netherlands. In the report they describe their vision for the Northern Netherlands by 2030 in order to reach climate goals under the Paris Agreement. Drivers for change in the region are large industrial potential, the Northern Netherlands as electricity hub and reduction in natural gas economy. The potential for hydrogen in the region is strengthened by the current infrastructure for electricity and production of energy. Biomass, wind and solar drive the production of hydrogen where it will be used for the production of ammonia, methanol, hydrogen transport to other regions and countries, mobility and grid balancing.

The PESTLE elements are well represented in the report. Hydrogen is seen as a potentially interesting energy carrier with need of political support and a changing legal system that enables a hydrogen economy. New business opportunities arise with hydrogen to replace the current natural gas market. On a social level, social acceptance, education, collaboration and further research are highlighted. The report does provide clear numbers of specific targets they want to reach, but no further quantitative information on the energy system is provided.

4.5.1.5 Berenschot

Berenschot conducted a study with the Energy Transition Model (ETM) (Ouden et al., 2018). The study highlights two extremes namely electrons versus molecules. The first model describes a system where full electrification takes place and molecules are solely used for long distant transport of energy. The other model describes the use of molecules where currently no electricity is used, e.g. industry. The electrons scenario describes a system with large scale capacity of RES solar and wind. Hydrogen is produced with electrolysis from wind and used in industry and powerplants. In the molecules scenario hydrogen is produced in SMR with CCS and used in industry and powerplants. The industry is to some extend electrified, while hybrid solutions are used in the built environment with CHP and green gas.

The ETM model does not cover political, social and legal consideration and for this reason are not discussed in the study. The approach of energy system modelling only covers economical, technical and environmental elements. From an economical perspective an electron scenario needs large capacity of RES to cover the peak demand, what leads to higher costs. From a technical perspective the energy efficiency is larger, since there are less conversion processes and CCS is not necessary. Hydrogen infrastructure between offshore wind, electrolysis and powerplants on hydrogen is needed. While the final energy demand in case of the molecule scenario is higher due to losses in conversion processes and CCS. The demand for natural gas stays similar to the current gas demand. A hydrogen infrastructure is needed for SMR with CCS. It should be noted, both scenarios do not exclude each other, but may arise complementary.

4.5.1.6 European Commission

'A clean planet for all' is a study published by the European Commission (EC) (2018). The 8 scenarios are electrification, hydrogen, power-to-X, energy efficiency, circular economy, combination, 1.5oC technical and 1.5oC sustainable lifestyle. The scenarios energy efficiency, circular economy, 1.5oC Sustainable Lifestyle are out of the scope of this research and for that reason not further analysed. Table 8 summarizes the selected scenarios based on the scenario building blocks. The differences between the scenarios can be found in this table, while the PESTLE analysis provides an overview of elements for all analysed scenarios, because the elements are not linked to specific scenarios. The difference between the scenarios is based on decisions made in Table 8.

Some interesting findings are summarized. The demand of electricity increases with demand for hydrogen caused by production of hydrogen by electrolysis. Additionally, the role of natural gas as a transition gas is larger in hydrogen scenarios. Hydrogen is present in the P2X scenario to produce other fuels. Furthermore, further research and development is necessary for hydrogen technologies, especially for performance and costs to scale up hydrogen deployment. When considering the scaling of e-fuels and hydrogen a dilemma occurs: in case the scaling is to small it may hamper the technology learning; when it is too big, there is need for a substantial additional need in supply side. From an economical perspective uncertainty is mentioned related to high investment costs, unpredictable levels of demand and regulatory uncertainty.

4.5.1.7 TKI Nieuw Gas

TKI Nieuw Gas provide a roadmap for hydrogen in the Netherlands (Gigler & Weeda, 2018). Instead of a visions/scenario for hydrogen, the potential of hydrogen and the challenges are discussed in detail. Markets for hydrogen are high temperature heat, mobility and transport, power and light and low temperature heat. TKI Nieuw Gas calculates a total potential for hydrogen in these sectors of 1600 PJ/y for which a capacity of 161 GW offshore wind should be installed with electrolysis.

Table 8 - Overview selection of scenarios. Scenario building blocks with long term strategy options.

	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Combination (COMBO)	1.5$_o$C Technical (1.5TECH)
Main Drivers	Electrification all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Cost-efficient combination of options from 2$_o$C scenarios.	Based on COMBO with more BECCS, CCS
GHG target in 2050	-80% GHG (excluding sinks) [“well below 2°C” ambition]				~100% GHG (incl.sinks) [“1.5$_o$C” ambition]
Major Common Assumptions	- Higher efficiency post 2030 - Deployment of sustainable, advanced biofuels - Moderate circular economy measures - Digitalisation		- Market coordination for infrastructure deployment - BECCS present only post-2050 in 2$_o$C scenarios - Significant learning by doing for low carbon technologies - Significant improvements in the efficiency of the transport system		
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.				
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Combination of most Cost-efficient options from “well below 2$_o$C” scenarios with targeted application (excluding CIRC)	COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating		
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some of LDVs	E-fuels deployment for all modes		
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution gird		Limited enhancement natural sink

Though TKI Nieuw Gas does not elaborate on visions/scenarios, PESTLE elements are well represented in the report. The key takeaways are (1) that hydrogen can enable reaching climate goals, (2) that an integral vision is needed, (3) all production ways can be used to reach a sustainable future, (4) action now enables hydrogen in the future and (5) stimulate innovation. The paper supports a deeper understanding of decision elements as a starting point for further development.

4.5.1.8 Fuel Cell & Hydrogen Joint Undertaking

As a response on the reports of the Hydrogen Council, McKinsey did a study for the Fuel Cell & Hydrogen Joint Undertaking (FCH) on the potential of hydrogen in Europe. The study has led to the Hydrogen Roadmap Europe. Some indicators are different between Europe and the rest of the world, i.e. in some European countries a strong natural gas infrastructure is present and European carbon pricing is implemented. As a vision the FCH formulated “exploiting Hydrogen’s unmatched versatility to empower Europe’s energy transition” (FCH, 2019, p.19). In other words, their ambition is to use hydrogen to enable the renewable energy system with storage and transport capabilities and to decarbonize end users by making Europe’s clean energy transition efficient and economically attractive. The FCH argues hydrogen can close to 50% of the gap between expected reductions and the 2₀C target by 2050. Various pathways are possible in the potential markets transportation, heating and power for buildings, industry heat, industry feedstock, and power generation (Figure 17). With Business As Usual (BAU) the penetration of hydrogen technologies will go much slower. Support and policy are needed in order to speed up the process.

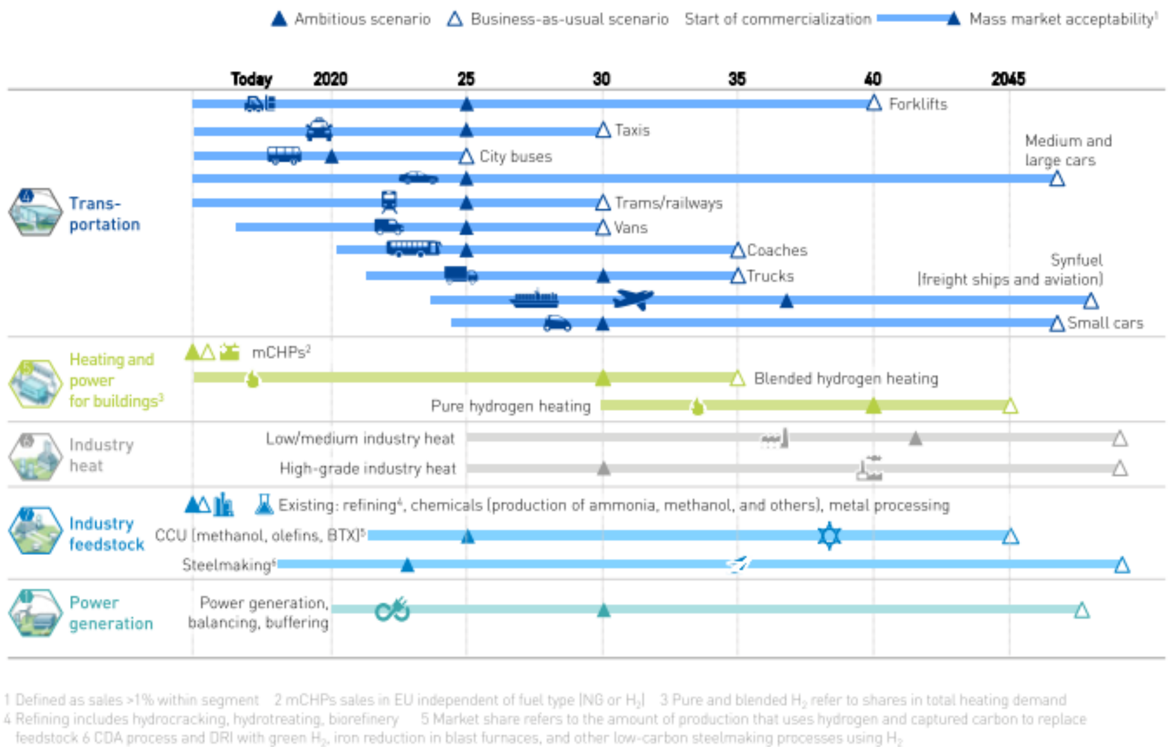

Figure 17 - Roadmap of technology readiness and scaling up to 2050

4.5.1.9 Provincie Zuid-Holland

After the specific vision statement for the Northern Netherlands a vision document for Zuid-Holland was published (Wijk et al., 2019). Zuid-Holland is famous for its industry with the Port of Rotterdam. The heavy industry offers challenges for a sustainable future and opportunities for a green hydrogen economy. Hydrogen can provide new industry for the economical region and enables sustainable alternatives that lead to decarbonization of the region by 2030.

The analysis for PESTLE-elements highlights the need of blue hydrogen in order to decarbonize industry and create scale. On the long-term green hydrogen will become cost competitive with grey (and blue) hydrogen. The current natural gas pipelines offer potential for future hydrogen infrastructure.

4.5.1.10 Gasunie & Tennet

Gasunie & Tennet (G&T) published the first infrastructure outlook for the Netherlands and Germany. The aim of the report is to provide scenarios to achieve 95% CO_2 emission reduction by 2050 compared to 1990 under the Paris Agreement. Although electricity may be an important energy carrier of the transition, it may not be the solution for all applications. In some cases, molecules are needed. Power to gas in the scenarios is seen as a cornerstone to fulfil major demand for energy and therefore electricity and gas grid become integrated. Three scenarios have been formulated, i.e. (1) local, (2) national and (3) international approach (Figure 18). The first scenario, local, has a decentral energy supply with PV, a central energy supply with wind and no energy exchange takes place with neighbouring countries. The second vision, national, aims for energy independency with centralized RES supply, power-to-gas and batteries for flexibility options and limited energy exchange with neighbouring countries. The third vision, international, has a focus on international energy exchange with limited support for extensive RES supply. In the scenarios there is a strong emphasis on the design with technical aspects. Especially economic and social indicators are lacking.

	Local	National	International
Power & Light	25% base-load savings through more efficient appliances. Substantial electrification of industry	25% base-load savings through more efficient appliances. Substantial electrification of industry	25% savings through more efficient appliances
Low-temperature heat	High penetration of heat grids and all-electric (restrictions on green gas, no H_2 distribution) Savings: 23%	High penetration of hybrid heat pumps burning H_2 (and green gas) (restrictions on green gas) Savings: 23%	High penetration of hybrid heat pumps burning H_2 and green gas (mild restrictions on green gas). Savings: 12%
High-temperature & feedstock industry	Circular industry and ambitious process innovation: 60% savings 55% electrification 97% lower CO_2 emissions	Circular industry and ambitious process innovation: 60% savings 55% electrification 97% lower CO_2 emissions	Biomass-based industry: 55% savings 35% biomass 14% electrification 95% lower CO_2 emissions
Passenger transport	100% electric	75% electric 25% hydrogen	50% electric 25% green gas 25% hydrogen
Freight transport	50% green gas 50% hydrogen	50% green gas 50% hydrogen	25% synthetic fuels 25% green gas 50% hydrogen
Renewables generation	84 GW solar 16 GW onshore wind 26 GW offshore wind	34 GW solar 14 GW onshore wind 53 GW offshore wind	16 GW solar 5 GW onshore wind 6 GW offshore wind
Conversion and storage	75 GW electrolysis 60 GW battery storage	60 GW electrolysis 50 GW battery storage	2 GW electrolysis 5 GW battery storage
Hydrogen	100 TWh domestic generation	158 TWh domestic generation	73 TWh import 4 TWh domestic generation
Methane	23 TWh domestic biomethane 35 TWh imported natural gas	46 TWh domestic biomethane 55 TWh imported natural gas	24 TWh domestic biomethane 72 TWh imported natural gas
Biomass			28 TWh import

Figure 18 - Table of the three Gasunie & Tennet scenarios with specifications.

Main takeaways from the study are that power to gas facilities should be well located for both gas as electricity infrastructure and in order to succeed, political willingness and a supporting regulatory framework are crucial. Economic, Social and Legal elements are missing in the scenarios.

4.5.2 Quantitative analysis visions

Some of the analysed reports have quantitative data on the energy system of 2050 and the role of hydrogen. The reports included in the quantitative analysis are Berenschot, European Commission, FCH and Gasunie & Tennet.

The final energy demands for each scenario for the Netherlands are shown in Figure 19. The precited final energy demand in PJ by 2050 is compared to the final energy demand of 2015. It is noticeable that all reports expect a decrease in final energy demand. Furthermore, the demand for hydrogen is compared to the final energy demand per scenario.

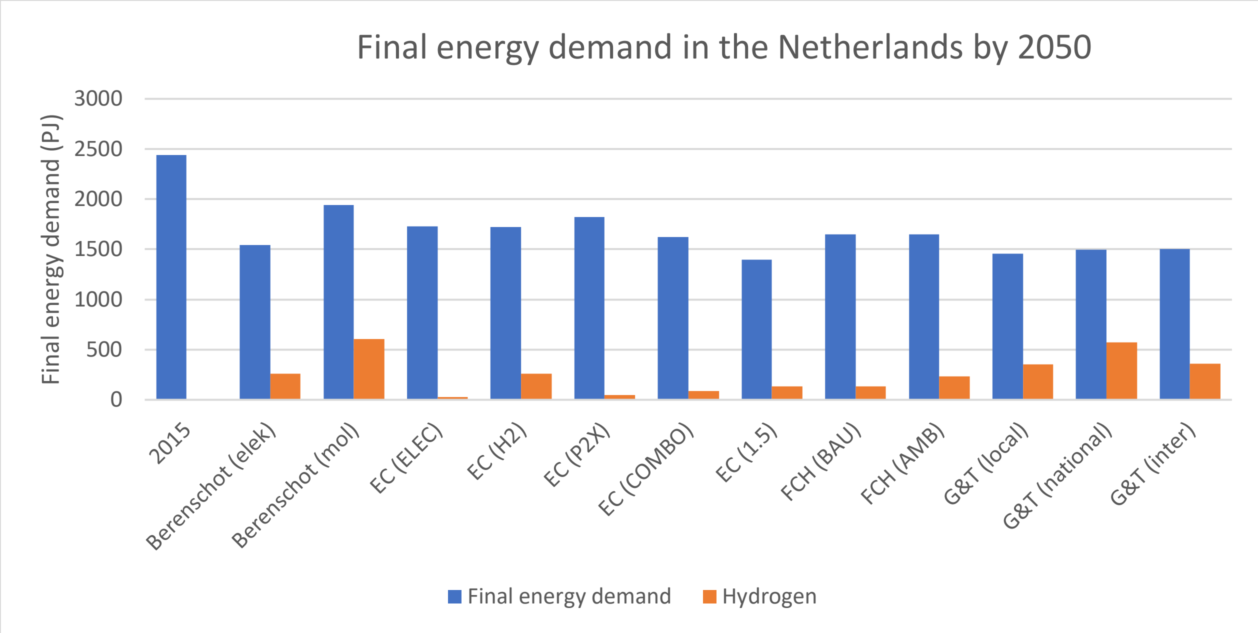

Figure 19 - Final energy demand with share of hydrogen for 2050. European studies are determined for Dutch final energy demand.

The European Scenarios, European Commission and FCH, are determined for the Netherlands.[5] The demand for hydrogen varies strongly. The European scenarios show well below 250 PJ hydrogen demand, while the Berenschot electron and the three G&T scenarios exceed 250 PJ. Especially the G&T national and the Berenschot molecule scenario shows large demands for hydrogen exceeding 500 PJ.

When comparing the electricity/electron scenarios of Berenschot and European Commission, a large difference can be found. Where in the Berenschot scenario, hydrogen plays a role for flexibility, in the European Commission scenario no demand for hydrogen is found.

Similar findings are seen in European scenarios for hydrogen with EC's P2X and FCH's AMB compared to Berenschot's molecule scenario. The European hydrogen scenarios stay well below 500 PJ, while the Berenschot scenario almost doubles the demand for hydrogen in the Netherlands. In case of the FCH scenario, the difference between distribution of sectors could play a role in strongly varying results, while in case of the EC scenario, sector specific conditions are taken into consideration.

[5] For the EC and FCH scenarios data for Europe was provided and not for the Netherlands. The EC provides detailed data on how different industries are compared. Therefore, all the results are specifically compared to the Netherlands (Appendix VII – Calculations European Commission). The FCH provided less detailed information of further development of the market and therefor the share of the Netherlands in Europe is used according to Eurostat (2015)(Appendix VIII – Calculations FCH)..

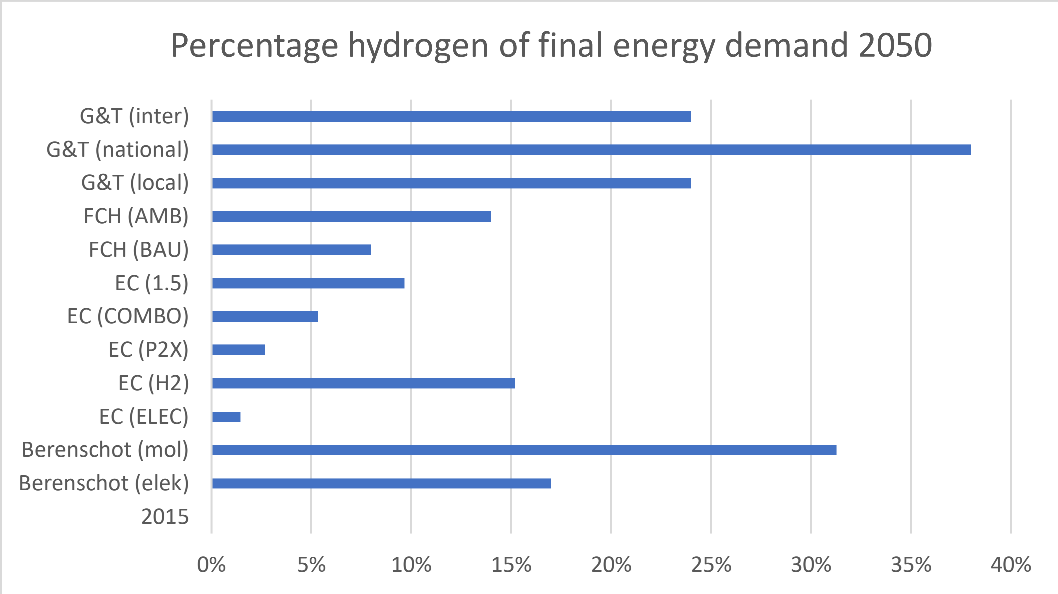

Figure 20 - Share of hydrogen of final energy demand the Netherlands in 2050.

What is interesting to see is that FCH BAU scenario shows a larger energy demand for hydrogen than all scenarios of EC without EC H2. FCH BAU though expects emergence of hydrogen technologies, but slower than the AMB scenario while the EC scenarios focus on alternative solutions than hydrogen.

The share of hydrogen compared to the final energy demand is shown in Figure 20. Comparing the share of hydrogen, again the scenarios of Berenschot and G&T show larger shares of hydrogen. The hydrogen focused scenarios in Europe (FCH AMB and EC H2) do not even come close to the Dutch scenarios. The range for European scenarios is 1-14% while the Dutch scenarios have a range of 17-18%.

When considering sectors, four main sectors for hydrogen have been identiefied as shown in Figure 21, i.e. built environment, industry, mobility and power balancing.

The demand for hydrogen in built environment is especially seen in the scenarios EC H2, FCH AMB, G&T national and G&T international. The G&T local shows a relatively lower demand for hydrogen in the Netherlands, due to stronger efficiency measures where the total demand of energy in built environment is smaller. Figure 19 shows a similar result for G&T local where the total final energy demand is lower than the other two G&T scenarios. The EC COMBO and 1.5 scenario, where various solutions and energy carriers are combined to an optimal energy system, hydrogen does play a role in the built environment, though less than hydrogen focussed scenarios.

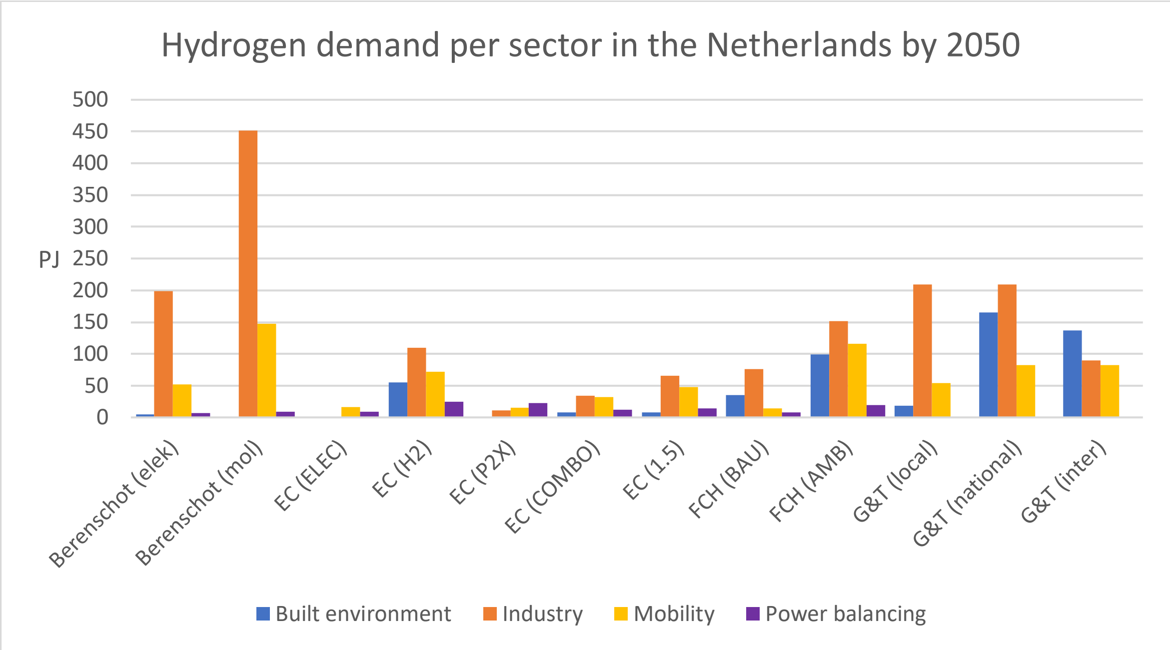

Figure 21 - Hydrogen demand per sector

Largest potential for hydrogen is seen for industry. Especially the Berenschot scenarios predict high hydrogen demands in industry. The EC P2X scenario shows very little demand for hydrogen in industry, due to other fuels/gasses that will play a role in decarbonization of industry. The EC COMBO and 1.5 do predict more hydrogen in industry because of the combination of electrification, P-t-X and hydrogen. In all three G&T scenarios hydrogen plays a role in industry, with a smaller demand for G&T international.

Mobility shows second largest potential for hydrogen in most scenarios. The Berenschot molecule scenario shows the largest potential for hydrogen, while the electron scenario shows less due to larger electrification of the transport sector. Second highest is the FCH AMB scenario where hydrogen in transport plays an important role. The G&T scenarios national and international show the same demand for hydrogen, while G&T local has a smaller demand due to 100% electrification of passenger transport. The EC 1.5 and EC H2 have similar outcomes as G&T national for the transport sector, with also a combination of electrification, hydrogen and other green fuels for transport.

Hydrogen for power balancing differs through scenarios. While it could be expected that the demand for power balancing is larger in electrification scenarios, often the hydrogen scenarios show larger demand for hydrogen in power balancing (Berenschot electrons & EC ELEC versus Berenschot molecules & EC H2). In the combined scenarios of EC, COMBO and 1.5 a small 15 PJ is expected for power balancing. No numbers are provider for power balancing in the

G&T scenarios. Though, electrolysis capacity is built for Power-to-hydrogen and hydrogen fired power plants are constructed varying between 1-4 GW capacity.

4.5.3 Vision comparison

Differences between the visions are explained in the vision comparison.

From the vision analysis, differences between the scenarios can be found. Differences are discussed in more detail, because they form the basis for further discussion on potential visions for hydrogen. The differences are on the market emphasis, the role of hydrogen in the system, the role of molecules in the system and the inclusion of import/an international system.

First, when examining the visions in time, the market emphasis changes over time. In the early visions (up until the report of PBL) the emphasis is put on the transport sector and built environment. Especially the transport sector with a role in heavy vehicles and passenger transport is seen as a great opportunity. Later, when electrical vehicles have taken a larger share in passenger transport, there is a potential shift to industry. Often is mentioned there are not many alternatives to decarbonize the industry as for other markets. Same counts for heavy vehicles, where electric vehicles are not powerful enough to decarbonize this market. When considering the quantitative analysis, industry shows the largest market potential for hydrogen followed by built environment and transport.

Second, electrification is often compared to molecules in the energy system. Studies from Berenschot, EC and Gasunie & Tennet compare systems with high level of electrification to systems with large integration of molecules, often hydrogen. From the studies it can be concluded that in a system with large demand for hydrogen and power-to-X, the demand for electricity will increase and more generation capacity should be in place. When comparing those studies to full hydrogen studies, we see other results. The report of the FCH on hydrogen in Europe provides a percentage that is comparable to the results of Gasunie & Tennet. When considering electron scenarios, the EC electricity scenario has a small share of hydrogen, while Berenschot electrons scenario shows potential for hydrogen due to power balancing and electrolysis capacity. On the other side, the studies of the Noordelijke Innovation Board and Provinice Zuid-Holland predict very large potential of hydrogen already by 2030. While those studies look at potentials at a current point in time, TKI Nieuw Gas determined the hypothetical potential of hydrogen in case a full market is changed into hydrogen. Those numbers should be seen as the maximum potential. When considering integrated approaches where no ‘winner’ is picked as energy carrier, hydrogen does play a substantial role. The EC combo, EC 1.5 Tech and all the G&T scenarios have some share of hydrogen in the final mix varying from 6-38%.

Third, in addition to the comparison between hydrogen and electricity, hydrogen is also compared to other molecules such as fossil fuels, biomass and methane. By Hisschemöller it is argued that the use of hydrogen produced of SMR with natural gas without CCS is not better than using direct fossil fuels in a combustion engine or by using biomass. While some may argue hydrogen is indeed a cleaner solution and with blue hydrogen production it does become cleaner. In favour of hydrogen over biomass, it is often argued for hydrogen less land use is necessary (EC). EC, PBL and Gasunie & Tennet mention other molecules may be used such as methane. While the production of methane needs hydrogen, the role in the final energy demand becomes smaller.

Fourth, a large difference between visions is the role of import and international dependency. Platform Nieuw Gas and PBL argue by using hydrogen, a national renewable energy system can be reached without international dependency. On the other side, the Noordelijke Innovation Board, Zuid-Holland and Routekaart Waterstof argue hydrogen could be seen as a good means for long distance transport. Hydrogen enables energy generation at RES resourceful location and transportation to areas with high energy demand such as the Netherlands. Gasunie & Tennet provide varying visions from no international interaction to large import of hydrogen and methane in order to balance supply and demand.

4.6 PESTLE analysis

As a result of the system analysis, actor analysis and vision comparison factors of the PESTLE-analysis can be determined. For hydrogen in the Netherlands, factors are discussed for Political, Economic, Social, Technical, Legal and Environmental indicators. The results are summarized in Table 9.

4.7 Conclusion System Orientation

The system orientation has shown the potential of hydrogen in industry, built environment, mobility and power sector. Various reports have been compared. The elements found in the comparison provide the starting point for vison construction.

The hydrogen demand in the Netherlands in the current system is already 100 PJ/year. With potential in industry, built environment, mobility and power sector the demand may rise over the following years where it may play a substantial role by 2050. Especially industry and transport are mentioned as sectors with large potential as mentioned in studies after 2010. Built environment shows increasing potential in studies of Gasunie & Tennet, FCH, EC H2, PBL, TKI Nieuw Gas and Noordelijke Innovation Board.

Main differences that were found between studies are the emphasis on sectors and markets, the role of hydrogen in the future energy system compared to electricity, the role of hydrogen in the future energy system compared to other molecules, and the inclusion of import and international interdependency to the future energy system.

The difference in of hydrogen in end use forms the basis for further elaboration, because it strongly influences the direction of the future energy system. Some visions such as FCH, Provincie Zuid-Holland, Noordelijke Innvoationboard, TKI Nieuw Gas, represent a hydrogen future with an increasing share of hydrogen by 2050. The studies describe hydrogen as a primary energy carrier. Other visions compare a system on hydrogen versus a system mainly on electricity (Berenschot, EC) where hydrogen is seen as a secondary energy carrier. Gasunie & Tennet highlight the importance of hydrogen even in a more electricity future and show this in three scenarios with high levels of hydrogen varying between 23% and 40% of the final energy demand. Same counts for the EC COMBO and 1.5 scenario. The integrated studies have hydrogen as primary and secondary energy carrier. This distinction will form the basis for the following chapters.

Table 9 - Summary of PESTLE analysis

Political	**Economic**	**Social**
• Aim clean affordable socially acceptable energy supply • Provide clear vision on hydrogen future • Gain technological leadership • Align demand, supply and infrastructure • Create clear policy framework with long term vision, stability, technologies, innovation, incentives and spatial planning • Overcome investment uncertainty without jeopardizing global competitiveness. • Use supportive policy measures	• Improve cost competitiveness electrolysis compared to grey and blue hydrogen • Reduce costs hydrogen technologies for application • Infrastructure of hydrogen is cost competitive compared to electricity infrastructure • Market coupling when electricity and hydrogen are connected. • Potential global hydrogen market • New economic opportunities with hydrogen • Limit investment uncertainty • Use policy instruments, e.g. subsidies, carbon tax and green certificates.	• Social acceptance for hydrogen in built environment • Social acceptance for hydrogen in transport sector • Similar customer experience with hydrogen • Demonstration projects for social acceptance • Education and training key for hydrogen transition
Technical	**Legal**	**Environmental**
• Need for energy carrier beside electricity • Further development of hydrogen technologies on - Costs in scale - Performance - Efficiency • Prove feasibility hydrogen technologies • Consider long duration of development process and innovation of technologies	• Create a stable regulatory framework with following elements: - Regulations and permit applications - Standards in legislation - Safety - Environmental regulations and spatial planning - Guarantees of origin - Regulations for grid - Supervision and enforcement • Identify players in a hydrogen market • Define hydrogen grid: public, private or hybrid. • Define market design hydrogen market	• Hydrogen enables reaching climate goals • Hydrogen improves air quality • Especially green hydrogen enables climate goals • Determine position of blue hydrogen • Determine position of hydrogen mixing with natural gas

5 Visions for hydrogen in 2050

Existing visions are compared in the previous chapter. The differences and PESTLE elements provide the basis for vision construction. In this chapter first three new visions will be constructed before a description per vision is provided. 5.1 Vision describes the process of selection for the visions. 5.2 Vision description provides an in-detail description of the three selected visions.

5.1 Vision construction

In vision construction, first extremes are determined as a basis to select three potential visions. Second, the three visions are linked to the existing visions to understand the relation. Third, a morphological chart is created based on the PESTLE-analysis and system orientation. Finally, elements are selected in the morphological chart for the three visions and checked on cross-consistency.

As a basis for the vision construction some objectives have been formulated, which should be incorporated in the described visions. First, the overall system configuration should lead to reaching the targets set by the Dutch government by 2050. Second, the visions describe the situation for the Netherlands, not a regional level. As stated by the Dutch government, the energy system should be affordable, etc.

From the vision comparison an important difference was the integration of hydrogen compared to electricity. In electricity visions, hydrogen often is used as a secondary energy carrier, while in molecule visions hydrogen is used as primary energy carrier. Distinction between visions has been made on hydrogen as primary or secondary energy carrier. Therefore, one extreme is an energy system with focus on electrification while another extreme is an energy system with focus on hydrogen in end-use. In between the two extremes a mixed vision can be selected.

Three levels of hydrogen integration have been selected as a basis for the scenarios:

1. Vision 1: All electric – electricity is preferred for every application. (hydrogen secondary carrier)
2. Vision 2: One integrated system – hydrogen and electricity will be applied in case proven better than the other carrier. (hydrogen both primary and secondary carrier)
3. Vision 3: Go hydrogen – emphasizes is placed on hydrogen for end use (hydrogen mainly primary carrier)

Table 10 - Visions of vision comparison related to selected visions for this study

Vision 1	Vision 2	Vision 3
Berenschot electrons EC ELEC	G&T scenarios EC Combo and EC 1.5	Berenschot molecules Provincie Zuid-Holland Noordelijke innovation board FCH

The visions of vision comparison form the basis for the vision selection. Table 10 provides an overview of the three visions with matching visions of selected studies.

Vision specific perspectives are distinguished with a morphological chart, including PESTLE, market, infrastructure and supply perspectives. The PESTLE elements are based on the PESTLE analysis in section 4.6. The elements for market, infrastructure and supply are determined based on section 4.1 and 4.2. Table 11 shows the morphological chart for possible visions. While many possible visions can be constructed with the morphological chart, elements are selected for only the three selected visions.

For each vision elements are selected in the morphological chart that match the three selected vision. Table 12 shows element selection for vision 1: All electric. The other morphological charts and cross consistency checks can be found in Appendix IX – Morphological charts visions.

All components are checked on consistency to make sure a viable vision is designed. In case of vision 1 all elements are compared. Elements that may interfere are discussed in more detail.

First, the combination of decentral infrastructure and central infrastructure may seem conflicting, however does not interfere with each other. The current hydrogen system has a decentral infrastructure in industrial clusters. This infrastructure stays the same. The central infrastructure connects wind farm, electrolysis facilities and storage facilities for power balancing purposes. Those infrastructures will exist alongside each other and therefore are consistent.

Table 11 - Morphological chart hydrogen visions

Production	Infrastructure	Markets	Political	Economic	Social	Technological	Legal	Environmental
Electrolysis	Decentral	Current market	Strong political support hydrogen	Electricity to natural gas ration high	Strong social support hydrogen	High development hydrogen technologies	Pro-active institutional change for hydrogen	Support green hydrogen to reach climate goals
SMR	Central	Industry high temperature heating	Moderate political support hydrogen	Electricity to natural gas ration moderate	Moderate social support hydrogen	Moderate development hydrogen technologies	Interactive institutional change for hydrogen	Support electricity to reach climate goals
SMR with CCS	International	Power balancing	Low political support hydrogen	Electricity to natural gas ration low	Low social support hydrogen	Low development hydrogen technologies	Passive institutional change for hydrogen	Support blue hydrogen to reach climate goals
Import		Built environment						Support biomass to reach climate goals
		Mobility heavy vehicles						
		Transport non-heavy vehicles						
		Alternative industrial processes						

Table 12 - Morphological chart with element selection for vision 1: All electric

Production	Infrastructure	Markets	Political	Economic	Social	Technological	Legal	Environmental
Electrolysis	Decentral	Current market	Strong political support hydrogen	Electricity to natural gas ration high	Strong social support hydrogen	High development hydrogen technologies	Pro-active institutional change for hydrogen	Support green hydrogen to reach climate goals
SMR	Central	Industry high temperature heating	Moderate political support hydrogen	Electricity to natural gas ration moderate	Moderate social support hydrogen	Moderate development hydrogen technologies	Interactive institutional change for hydrogen	Support electricity to reach climate goals
SMR with CCS	International	Power balancing	Low political support hydrogen	Electricity to natural gas ration low	Low social support hydrogen	Low development hydrogen technologies	Passive institutional change for hydrogen	Support blue hydrogen to reach climate goals
Import		Built environment						Support biomass to reach climate goals
		Mobility heavy vehicles						
		Transport non-heavy vehicles						
		Alternative industrial processes						

Second, low political support, low social support hydrogen and passive institutional change for hydrogen may be inconsistent with support green hydrogen to reach climate goals. The level of support for green hydrogen is from a different perspective. In case of political, social and institutional the basis comes from government bodies and society. The support for green hydrogen to reach climate goals is supported by utilities and offshore wind farm investors. A business case for hydrogen occurs to support integration of RES in the energy system. Therefor support of the government and society is not crucial in hydrogen as secondary energy carrier.

Final, low development hydrogen technologies and support green hydrogen to reach climate goals may seem inconsistent. With support for green hydrogen to reach climate goals, moderate to high technological development could be expected. The problem in this situation is the lack of institutional and governmental support to further develop hydrogen technologies. Electrolysis and hydrogen fired power plants are implemented, but the scale is limited. Without the support of the government and limited development in markets, technological development of hydrogen technologies will be low.

5.2 Vision description

The three selected visions are described on three elements: (1) narrative description of the hydrogen system, (2) technological deployment expressed in quantitative indicators, and (3) system diagrams that represent the vision. The quantitative indicators are shown in Table 13.

The values in Table 13 are based on findings of section 4.1 and section 4.2. The current demand for hydrogen is around 100 PJ/year (DNV GL, 2017b). New industry is calculated based on predicted demand for 2050 (BlueTerra, 2018; CE Delft, 2015). Vision 2 includes only very high temperature heat, while vision 3 includes all high temperature heat. Transport predictions for 2050 has been calculated with changes of the transport sector by the European Commission (2018) compared to the transport sector in the Netherlands of 2015 (CBS, PBL, RIVM, & WUR, 2018). In vision 2, only heavy vehicles are included, while for vision 3 passenger transport is added. Built environment is determined with heat demand predictions for 2050 of CPB & PBL (2016). The central scenario has formed the basis. Vision 2 includes 5% of hydrogen in heat demand and vision 3 20%. For storage, the demand of the European Commission (2018) is used as a basis for demand for storage. The local and national scenarios of G&T provided the distribution of hydrogen capacity with batteries.

Table 13 - quantitative summary of visions.

	Vision 1	Vision 2	Vision 3
Demand			
Total final energy demand hydrogen	**100 PJ**	**376 PJ**	**649 PJ**
Of which existing industry[1]	100 PJ	100 PJ	100 PJ
Of which new industry	-	200 PJ	344 PJ
Of which transport	-	69 PJ	147 PJ
Of which built environment	-	7,25 PJ	58 PJ
Production			
Min installed capacity electrolysis [2]	4,0 GW	14,6 GW[3]	30 GW[3]
Min installed capacity SMR with CCS [4]	-	8,7 GW	10 GW
Import interconnection	-	-	13,7 GW
Flexibility			
Demand power sector	35 PJ	25 PJ	-
Min capacity electrolysis for storage [2, 5]	6,5 GW	5,4 GW	-
Installed capacity hydrogen power plant [6]	31 GW	17 GW	-

[1] 20% of current hydrogen demand is by-product in industry. [2] Efficiency of electrolysis is set on 64% (IEA, 2019). [3] Calculations for wind are based on 4200 of 8760 full load hours. (average of ECN (2016)). [4] Efficiency of SMR is set on 76% (IEA, 2019). [5] For calculations on storage, 2000 of 8760 full load hours are used. [6] For electricity generation 500 of 8760 full load hours are used.

Figure 22 compares the constructed visions with the analysed visions. For all constructed visions, the hydrogen feedstock demand is included in industry. Vision 1 is the scenario where hydrogen is used as secondary energy carrier in power balancing. In the scenarios Berenschot elek and EC ELEC compared to vision 1, lower values are found for power balancing purposes of hydrogen. This could be caused due to the usage of data on hydrogen storage of EC and G&T combined, because they provided the best input for power balancing calculations.

In vision 1, hydrogen is used for power balancing. The existing hydrogen supply is replaced by electrolysis. Demand for storage is determined based on EC (Elec) and G&T national. In vision 2, the existing hydrogen supply is provided with CCS. Electrolysis is scaled to a total of 20 GW what leaves leftover demand of hydrogen for additional SMR with CCS capacity.

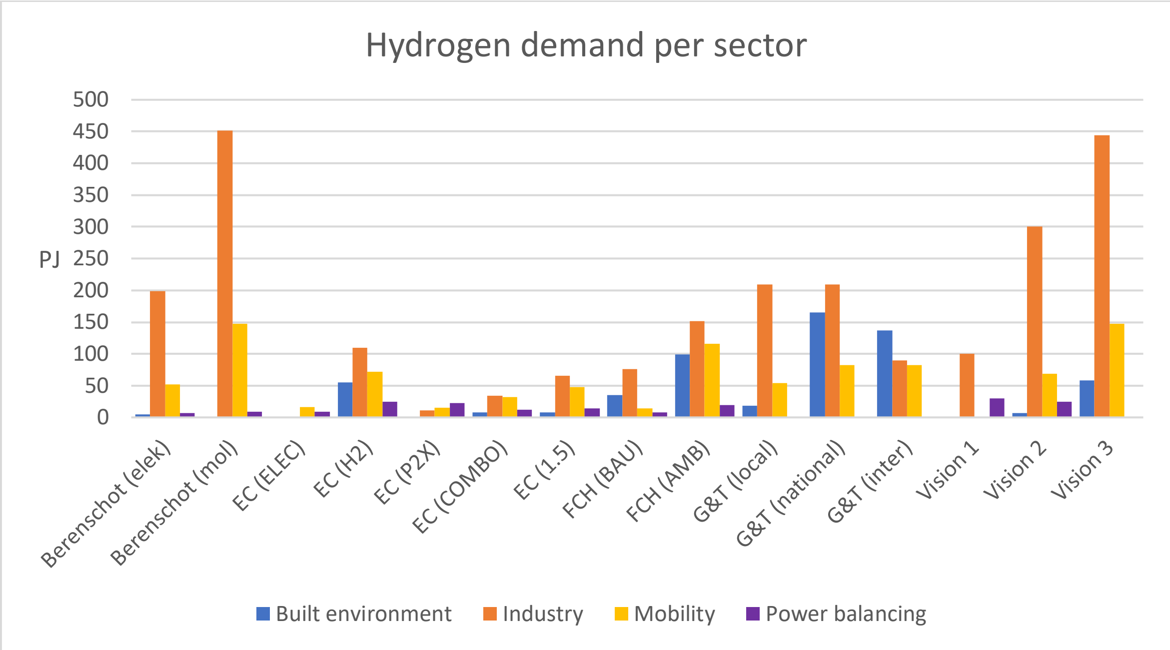

Figure 22 - Visions compared to scenarios for hydrogen demand per sector

A part of high temperature heating is taken care of by hydrogen. Other heat sources are used for the other heat demand. In transport, hydrogen only plays a role for heavy vehicles, passenger transport is fully electrified. 5 % of heat demand in built environment is taken care of with hydrogen. For vision 3, hydrogen is used to its full potential. All high temperature heat demand in industry is covered with hydrogen, same for heavy vehicles and long-distance passenger transport (current gasoline vehicles). In the built environment a share of 40% is covering the heat demand of hydrogen.

What is interesting to see is that especially for vision 2 the demand for industry is larger than EC 1.5, EC COMBO and the G&T scenarios. If the current hydrogen demand is taken away, the total demand that is left is comparable with G&T local and G&T international (around 200 PJ hydrogen demand in industry). Vision 2 shows similar results for transport, varying between the G&T local scenario and the G&T national and international scenarios. The demand for transport is larger than EC COMBO and EC 1.5 compared to vision 2, while the difference between EC 1.5 and vision 2 is only 20 PJ. Results for built environment are roughly the same as EC 1.5 and EC COMBO. The difference for built environment is much larger with the G&T scenarios.

Vision 3 shows similar results for industry as the Berenschot molecule scenario. The EC H2 and FCH AMB have small hydrogen demands in industry. In transport, FCH AMB and

Berenschot molecules match the demand for hydrogen. In case of built environment, the FCH AMB and EC H2 scenarios have similar results for hydrogen demand.

5.2.1 Vision 1: All Electric

This section provides the narrative description of vision 1.

Vision 1: All Electric describes a future system for the Netherlands in 2050 where electricity is seen as the main energy carrier for the energy transition as shown in Figure 23. RES such as solar and wind are installed in large capacity on the North Sea and on rooftops. Therefore, electricity generation becomes both central and decentral. Due to the preference of electricity no political, legal and social support for hydrogen is there. Electrification is reached in all applications where possible. Because peak demand needs to be met by RES, large capacity is needed to cover this demand. The often-occurring surplus can be used for hydrogen production via electrolysis. This green hydrogen is both used for the industry application as for a backup in case the fluctuating generation of RES does not match the demand. Since electricity is seen as the solution to solve climate change and green hydrogen can support implementation of large RES capacity there is support on an environmental level for hydrogen. Current SMR capacity is replaced by electrolysis. Thus, hydrogen is used in power plants. Storage of hydrogen takes place in salt caverns. As a result of lack of support and lack of hydrogen markets, technological development of hydrogen technologies is low.

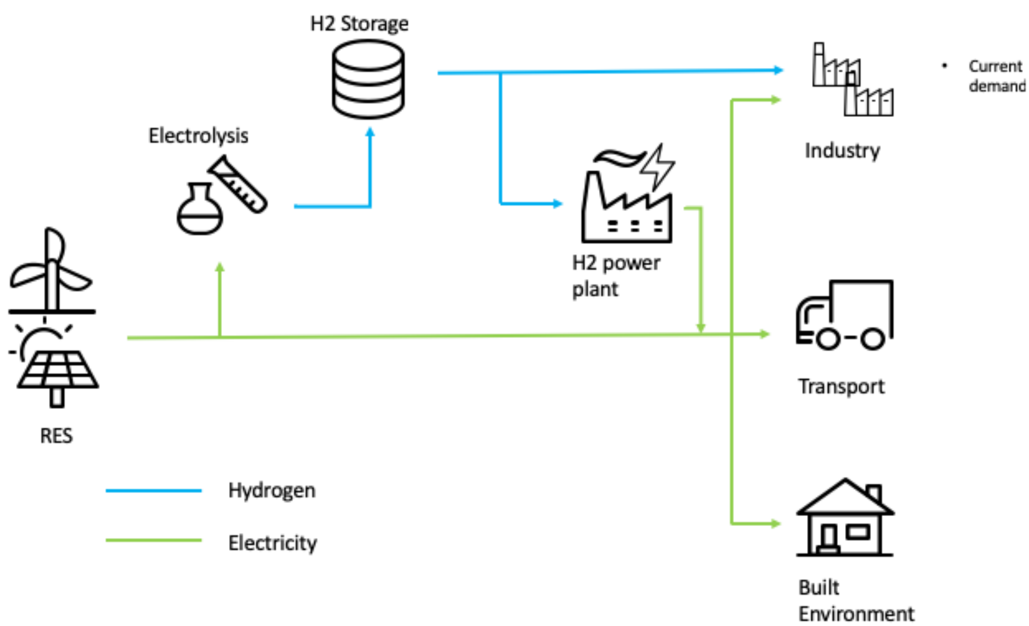

Figure 23 - System diagram of vision 1: All Electric

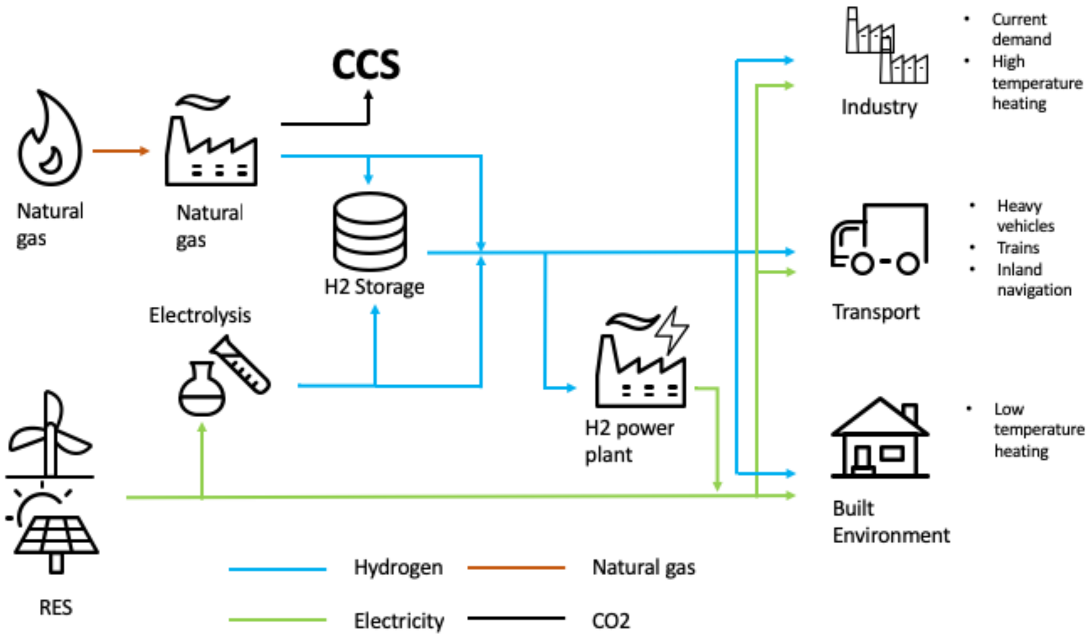

Figure 24 - System diagram of vision 2: One integrated system

5.2.2 Vision 2: One integrated system

One integrated system supports the vision the future will exist of many energy carriers. In this vision hydrogen and electricity are chosen as main energy carriers as shown in Figure 24. Electricity is produced via RES. Hydrogen will be used where proven better than other technologies. In that case, decarbonization of industry is very important. In case of transportation, EV are not a good solution for heavy vehicles. That is where hydrogen will play an important part. Hydrogen is preferred in this scenario over biomass or e-fuels. In addition, for the built environment, old residential buildings have low energy efficiency potential and alternative heating sources are not available. Therefor hydrogen is used for heating in old residential buildings. Because the market for hydrogen will grow, it is questioned whether the RES capacity is able to supply the hydrogen market. The infrastructure is decentral in built environment and current market. For high temperature heating, storage and transport a central hydrogen infrastructure is designed. As a solution blue hydrogen is used as an alternative. From an environmental perspective, green hydrogen, electricity and blue hydrogen are seen as solutions to reach climate goals. Moderate political and social support is necessary to facilitate the sectoral changes. Furthermore, interactive institutional change takes place in order to respond to the growing demand of hydrogen. Hydrogen applications and electrolysis comes up to a certain level what demands moderate technological development of hydrogen technologies.

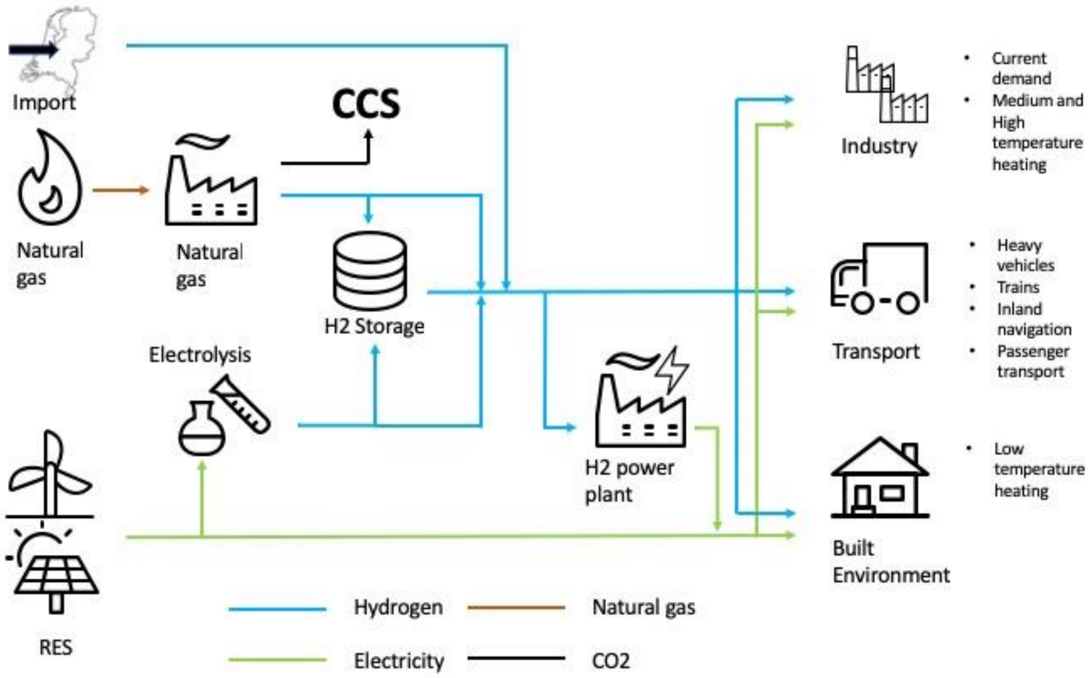

Figure 25 - System diagram of vision 3: Go Hydrogen

5.2.3 Vision 3: Go Hydrogen

Vision 3: Go Hydrogen represents a system where hydrogen is exploited to its full potential as shown in Figure 25. Hydrogen is seen as the solution to overcoming climate goals with both green and blue hydrogen as import. Full political and social support is shown for the technology in such a way the costs go down strongly, and the technology matures quickly. By 2050 hydrogen is active in many markets. Institutional change is done proactive to guide changes to the hydrogen system and new hydrogen markets. In industry hydrogen plays a role in high temperature heating and the current market. In transport besides heavy vehicles, hydrogen is also implemented for passenger transport. The vision is built on the principle, if you implement hydrogen in some residential areas, it may become interesting for other areas as well. Thus, hydrogen is broader implemented in the built environment by 2050 as heating source. Furthermore, hydrogen shows potential to cover peak demand in decentral heating systems. The use of hydrogen in power balancing is small, since the demand for hydrogen increases the overall demand for electricity. To cover the increasing demand, blue hydrogen production plays an important role in the system. In order to allow for such hydrogen demand and generation, a large infrastructure is in place to distribute hydrogen through the Netherlands. Due to the large demand for hydrogen and limited RES capacity, import of hydrogen from high RES potential countries is large. Transport of hydrogen over long distances take place via pipelines, boats and trucks.

5.3 Conclusion vision for hydrogen in 2050

As a result of vision construction, the discussion on electricity and hydrogen is highlighted. The PESTLE-analysis and vision comparison have formed the basis of the morphological analysis. As a result, the following three visions have been designed:

1. Vision 1: All electric
2. Vision 2: One integrated system
3. Vision 3: Go hydrogen

Because the three visions are based on preliminary studies for hydrogen in the Netherlands and Europe, they show similar results in hydrogen demand as these studies. Several levels of inclusion for hydrogen as primary and/or secondary energy carrier are considered through the visions with varying political, social and legal support. The three constructed visions form the basis for the interviews conducted with experts and stakeholders.

6 Backcasting

This chapters summarizes the backcasting results of the interviews conducted with experts and companies. All the interviews have been analysed, the results gathered and aggregated to provide an overview of WHAT-HOW-WHO analysis, drivers and barriers. During the interviews, the visions were shown or explained to interviewees before answering questions on changes, barriers and drivers. Section 6.1 summarizes the non-vision related findings of interviews. Section 6.2, section 6.3 & section 0 summarize the vision specific findings per vision. The drivers and barriers are described in section 6.5 & section 6.6. Section 6.7 provides an overview of diversity in perspectives of interviewees. Finally, the chapter is concluded in section 6.8.

All WHAT-HOW-WHO changes have been assigned to visions. The WHAT-HOW-WHO changes have been grouped under cultural, structural and technical changes.

6.1 Non-vision related findings

Some changes in the interviews are not related to a single vision, but are relevant for all visions. Those changes are summarized in this section. First overall changes in culture will be discussed, then social changes and finally technical changes.

6.1.1 Cultural

The cultural aspects of a vision consist of behavioural change and educational change. The cultural changes of non-vision related findings are shown in Table 14. Social acceptance is important within society. Especially in context of business behaviour change in attitude is required. Businesses need to enable their working environment in order to build a transition towards hydrogen. Furthermore, a hydrogen infrastructure beyond the existing infrastructure needs to be designed to transport the hydrogen to storage facilities. Public acceptance is crucial in realising this in every vision.

From an educational perspective, there are two changes. First, programmes should be designed to make society acquainted with hydrogen in the energy system. Second, the educational system should create courses to train future employees for constructing and operating hydrogen systems of the future.

Table 14 - Cultural changes non-vision related findings

	What	How	Who
Behavioural change	C0.1 & C0.2 Corporate culture C0.3 Social acceptation of hydrogen	C0.1 Enable corporate support by gaining trust and support within company of board of directors in such a way they will support employees and projects in difficult times. C0.2 Stay critical on hydrogen (challenging in vision 3). C0.3 Social acceptance of hydrogen underground	C0.1 & C0.2 All companies that participate in the hydrogen economy or are involved in hydrogen projects. C0.3 Government, municipalities
Educational change	C0.4 – C0.7 knowledge on hydrogen technologies	C0.4 Create research programs to gain more knowledge on hydrogen technology, its application and implementation. C0.5 Create demonstration programs to facilitate demonstrations. With an organized approach, knowledge and social acceptance can increase. C0.6 Educate people in order to realise new economies with studies that teach on technologies and implementation. C0.7 Educate people in construction and implementation of electrolysis to enable construction and operation on a large scale.	C0.4 & C0.5 Universities, knowledge institutes, sector specific actors dependent on program, authorities dependent on program. C0.6 & C0.7 Educational institutes, ministry of education.

6.1.2 Structural

The structural aspects of a vision consist of institutional change, organisational change, legal change and economical change. The structural changes of non-vision related findings are shown in Table 15. To enable hydrogen institutional changes are needed, such as tenders, subsidy schemes and regulations. Decisions have to be made on the market design of hydrogen and property rights of the system in order to enable hydrogen. The organisational perspective focusses on how to structure realisation with various actors. Collaboration and guidance are key in organisational changes. From a legal perspective, adjustments need to be made in regulations. Contracts are needed that legally bond actors. Furthermore, boundaries of the hydrogen system should be selected. In order to make hydrogen technologies economic feasible, subsidies and taxes need to be provided. Furthermore, long term investment plans are necessary to decrease investment risks.

Table 15 - Structural changes non-vision related findings

	What	How	Who
Institutional change	S0.1 Governmental direction S0.2 Enable hydrogen S0.3-S0.5 Set institutional description of hydrogen S0.6 prevent moving companies S0.7 Enable electrolysis	S0.1 Determine KPIs on hydrogen development in order to monitor performance. S0.2 Determine preconditions in tenders and subsidy schemes for hydrogen projects to allow for a variety of projects. S0.3 Determine the amounts of quality for hydrogen needed and what quality has largest potential for scale. S0.4 Determine the number of infrastructures needed with varying quality of hydrogen. S0.5 Determine whether cleaning stations are necessary in hydrogen grid. S0.6 Stimulate companies to invest in the newest, most efficient and most sustainable technologies with support schemes and regulations. S0.7 Create tenders for electrolysis capacity.	S0.1 Government S0.2 Government, RVO S0.3 - S0.5 TSO, DSO, hydrogen suppliers and government. S0.6 Government S0.7 Government, RVO
Organisational change	S0.8 Gain leadership S0.9 – S0.10 Enable collaboration	S0.8 Take leadership in guiding smaller actors in collaborations.	S0.8 Government S0.9 Actor in lead of a project in combination with included actors.

	S0.11 Risk reduction S0.12 Long term planning	S0.9 Select essential partners for projects to reach the MVC (minimal viable coalition) in chain solutions. S0.10 Facilitate collaborations between actors that can facilitate 'New' industry for 2050 with circular bio-based economy. S0.11 Divide risk between partners to make every actor responsible for success via contractual commitments. S0.12 Create company agendas for 20, 30 and 40 years from now.	S0.10 Government and relevant actors specific to project. S0.11 Actors in MVC. S0.12 all corporate companies.
Legal change	S0.13 Decrease grey hydrogen S0.14 & S0.15 Enable hydrogen projects	S0.13 Set regulations on grey hydrogen production on GHG emissions and efficiency to improve technology and nudge companies towards CCS. S0.14 Draw up clear and consistent contracts in projects that no actor can easily step back. S0.15 Draw up clear and consistent conditions actors are forced to control safety and cost efficiency.	S0.13 Government, grey hydrogen producers. S0.14 Coalitions and actors involved in projects. S0.15 DSO, TSO, coalitions and actors involved in projects.
Economical change	S0.16 Decrease grey hydrogen S0.17 Support clean industry S0.18 Enable hydrogen infrastructure	S0.16 Set a carbon tax for carbon emissions that makes grey hydrogen production more expensive. S0.17 Build subsidy schemes around circular bio-based chains located in the Netherlands S0.18 Design long term investment plans for infrastructure with integration of hydrogen, electricity and natural gas in order to decrease infrastructure uncertainty.	S0.16 Government S0.17 Government, RVO S0.18 Government, TSO, DSO, hydrogen suppliers.

6.1.3 Technical

The technical aspects of a vision consist of infrastructural change, production change, application change and R&D change. The technical changes of non-vision related findings are shown in Table 16.

The current infrastructure needs adjustments in order to facilitate an increase of hydrogen. The size and design of the infrastructure depends on the visions. Every vision uses green hydrogen production. Since electrolysis is still limited, it should be scaled-up to meet the outcome of the visions. Furthermore, some applications overlap. Storage for hydrogen should be enabled and circular bio-based value chains should be designed.

To facilitate the technical changes in the system, R&D is needed to gain more knowledge on the topics. Focus area for research are efficiency, costs and safety of electrolysis, hydrogen power plants, hydrogen storage in both salt caverns and other methods, and hydrogen infrastructure possibilities in natural gas grid.

Table 16 - Technical changes non-vision related findings

	What	How	Who
Infrastructure	T0.1 & T0.3 Enable hydrogen projects T0.2 Transform natural gas grid	T0.1 Construct infrastructure along development of supply and demand. T0.2 Adjust natural gas grid to allow for hydrogen to be transported. T0.3 Construct infrastructure for potential hydrogen demand in future.	T0.1 & T0.3 DSO, TSO, hydrogen suppliers. T0.2 DSO, TSO
Production	T0.4 – T0.7 Enable large scale electrolysis	T0.4 Make electrolysis production industrial. T0.5 Use more efficient materials in electrolysis production. T0.6 Scale up electrolysis by slowly go from 100 MW to larger capacities. T0.7 Redesign supply chain of electrolysis production with optimized processes.	T0.4, T0.5 & T0.7 Electrolysis producer. T0.6 Hydrogen suppliers, electrolysis investors, electrolysis manufacturers, industry that uses electrolysis.

Application	T0.8 Enable multiple energy carriers T0.9 Facilitate flexibility T0.10 & T0.11 Enable carbon utilization T0.12 & T0.13 Enable hydrogen storage	T0.8 Develop system for multiple energy carriers. T0.9 Construct needed demand for flexibility as addition on baseload near source. T0.10 Use hydrogen to create new products with carbon emissions (ecosystem). T0.11 Construct and design chains with a circular bio-based mind set. T0.12 Construct cross boarder storage capacity in salt caverns. T0.13 Construct short term storage capacity in tanks.	T0.8 Government, utilities, DSO, TSO. T0.9 Government, utilities, TSO, electrolysis investor. T0.10 Industrial coalition T0.11 Industrial coalition, TSO, DSO, companies, government. T0.12 & T0.13 TSO, Government, utilities, storage companies.
R&D	T0.14 Monitor technologies T0.15 Development electrolysis T0.16 Development hydrogen power plants T0.17 Development infrastructure T0.18 Development hydrogen storage	T0.14 Monitor hydrogen technologies and alternatives to compare them continuously in order to determine which one is best in what situation. T0.15 Research on cost, efficiency, safety and scale electrolysis. T0.16 Research on cost, efficiency and safety hydrogen power plants T0.17 Research on hydrogen in natural gas grid and hydrogen infrastructure T0.18 Research on hydrogen in salt caverns and other storage technologies.	T0.14 - T0.18 Government, knowledge institutes, universities, companies

6.2 Findings vision 1

Changes described in this section relate to vision 1. First overall changes in culture will be discussed, then social changes and finally technical changes.

6.2.1 Cultural

The cultural aspects of a vision consist of behavioural change and educational change. The cultural changes of non-vision related findings are shown in Table 17.

For vision 1 the focus in behaviour change is on current industry and power sector. Changes that must occur focus on current hydrogen industry and utilities. Educational changes will enable the construction of necessary hydrogen production and storage.

Table 17 - Cultural changes vision 1

	What	How	Who
Behavioural change	C1.1 Social acceptance hydrogen C1.2 & C1.3 Company culture and actions	C1.1 Enable acceptance of hydrogen as power supply in electricity sector of society with public education. C1.2 Stimulate companies to incorporate hydrogen in wind plans. C1.3 Stimulate current hydrogen industry to go green	C1.1 Government, utilities, society C1.2 Government, companies involved wind farms, electrolysis companies C1.3 Hydrogen suppliers and operators
Educational change	C1.4 knowledge on hydrogen technologies	C1.4 Educate people in construction and implementation of electrolysis in utilities.	C1.4 Educational institutes, ministry of education

6.2.2 Structural

The structural aspects of a vision consist of institutional change, organisational change, legal change and economical change. The structural changes of non-vision related findings are shown in Table 18.

Structural changes in vision 1 are tenders for electrolysis and subsidies. In that way hydrogen is enabled in storage, as fuel and for electrolysis. No organisational changes can be specifically assigned to vision 1.

Table 18 - Structural changes vision 1

	What	How	Who
Institutional change	S1.1 Enable hydrogen for flexibility S1.2 Enable electrolysis S1.3 Enable hydrogen storage	S1.1 Include hydrogen in off shore wind tenders as balancing mechanism or use the hydrogen for other applications. S1.2 Design tenders for electrolysis. S1.3 Design tenders for storage in salt caverns.	S1.1 – S1.3 Government, utilities, tender actors, TSO, electrolysis producers, electrolysis operators.
Legal change	S1.4 Enable hydrogen for flexibility	S1.4 Adjust regulations to allow for hydrogen in utilities.	S1.4 Government
Economical change	S1.5 Enable electrolysis	S1.5 Provide subsidies for electrolysis projects to ensure the business case.	S1.5 Government, RVO, electrolysis producers, electrolysis operators, investors.

6.2.3 Technical

The technical aspects of a vision consist of infrastructural change, production change, application change and R&D change. The technical changes of non-vision related findings are shown in Table 19.

Technological changes that occur in vision 1 are mainly focused on electrolysis. The electricity grid and hydrogen grid will become interconnected in order to allow flexibility for electricity via hydrogen. The current hydrogen production will be fully replaced by green hydrogen. To enable flexibility, storage of hydrogen needs to be realised. Specific research for vision 1 is the realisation of hydrogen storage on large scale.

Table 19 - Technical changes vision 1

	What	How	Who
Infrastructure	T1.1 Design power balancing system	T1.1 Use electrolysis as a conversion unit between electricity and hydrogen to integrate the grids.	T1.1 TSO, utilities

Production	T1.2 Decrease grey hydrogen	T1.2 Replace grey hydrogen production by green hydrogen.	T1.2 Electrolysis investors, hydrogen suppliers.
Application	T1.3 Design power balancing system T1.4 – T1.5 Allow for hydrogen storage	T1.3 Design flexible system around electrolysis to enable its flexibility. T1.4 Use surplus of electricity to convert to hydrogen. T1.5 Construct hydrogen storage facilities in salt caverns.	T3.4 Electrolysis chain investors and manufacturers T4.2 TSO, utilities, electrolysis owner. T1.7 TSO, Government, utilities, storage companies.
R&D	T1.6 Development storage in salt caverns	T1.6 Determine need for storage in salt caverns.	T1.6 TSO, Government, utilities, storage companies.

6.3 Findings vision 2

Changes described in this section relate to vision 2. First overall changes in culture will be discussed, then social changes and finally technical changes.

6.3.1 Cultural

The cultural aspects of a vision consist of behavioural change and educational change. The cultural changes of non-vision related findings are shown in Table 20

In vision 2 various elements come together, i.e. hydrogen in transport, built environment, industry and power balancing. This demands broad changes. Social acceptance plays a large role in built environment and transport. Behavioural change needs to be triggered. Educational changes describe demonstration projects to show how certain projects work in built environment and for heavy transport. These demonstrations should raise awareness and willingness to participate in cultural change.

Table 20 - Cultural changes vision 2

	What	How	Who

Behavioural change	C2.1, C2.2 & C2.4 Social behaviour regarding environment and hydrogen C2.3 Enable hydrogen in built environment. C2.5 & C2.6 Corporate culture	C2.1 Make decisions based on rational and not on social pressure of public by what solutions are technological feasible and cost efficient before exploiting markets with less potential. C2.2 Shift focus of carbon reduction to reaching a circular bio-based energy system with a result carbon reduction by advertising on other strategy both politically as socially. C2.3 Gain trust and support of regulating actors in built environment for hydrogen heating. C2.4 Stimulate behaviour to increase insulation measures to households with taxes. C2.5 Stimulate companies to incorporate hydrogen in wind plans. C2.6 Stimulate current hydrogen industry to go green	C2.1 Municipalities, government, DSO, TSO, public, companies involved in hydrogen projects. C2.2 Government, municipalities, industry, NGOs, environmental advisory groups. C2.3 ACM, SODM, Ministry of EZK. C2.4 Government, DSO, hydrogen producers. C2.5 Government, companies involved wind farms, electrolysis companies C2.6 Hydrogen suppliers and operators
Educational change	C2.7 – C2.9 Knowledge on hydrogen technologies	C2.7 Design demonstration projects in built environment to show to public how heating of houses can be done with hydrogen. C2.8 Design demonstration projects with hydrogen for heavy vehicles with refuelling stations. C2.9 Educate people in construction and implementation of electrolysis in utilities.	C2.7 DSO, municipality, residential area, home owners, boiler company, hydrogen producer, hydrogen distributer, housing corporation. C2.8 Heavy vehicle producers, hydrogen refuelling producers and operators, transport companies local/regional authority, ministry of infrastructure. C2.9 Educational institutes, ministry of education

6.3.2 Structural

The structural aspects of a vision consist of institutional change, organisational change, legal change and economical change. The structural changes of non-vision related findings are shown in Table 21.

Institutional changes enable electrolysis, infrastructure, storage and wind combined with hydrogen. Decisions have to be made for hydrogen import whether grey hydrogen import is allowed. Organisational changes enable collaborations between necessary stakeholders. On a legal level, regulations for carbon emission, European alignments, hydrogen in utilities and definition of hydrogen infrastructure are necessary. Economical changes focus on subsidies and financial incentives to enable clean production and hydrogen in sectors power, transport, industry and built environment.

Table 21 - Structural changes vision 2

	What	How	Who
Institutional change	S2.1 Enable hydrogen for flexibility S2.2 Enable electrolysis S2.3 Enable hydrogen storage	S2.1 Include hydrogen in off shore wind tenders as balancing mechanism or use the hydrogen for other applications. S2.2 Design tenders for electrolysis. S2.3 Design tenders for storage in salt caverns.	S2.1 Government, utilities, tender actors, TSO, electrolysis producers, electrolysis operators. S2.2 & S2.3 Government, utilities, tender actors, TSO, electrolysis producers, electrolysis operators.
Organisational change	S2.4 Facilitate strong collaborations	S2.4 Enable support to invest in hydrogen infrastructure of the future by taking risk away.	S2.4 Government, DSO, TSO, hydrogen suppliers.
Legal change	S2.5 Enable hydrogen infrastructure S2.6 Enable storage hydrogen S2.7 Align with EU	S2.5 Define if hydrogen infrastructure stays public or private. S2.6 Set regulations on carbon emission storage in order to limit the storage potential. S2.7 Align law and regulations EU countries by working towards	S2.5 Government, DSO, TSO, hydrogen suppliers. S2.6 Government S2.7 European Commission, European countries.

	S2.8 Enable hydrogen for flexibility	the same goal with country specific path. S2.8 Adjust regulations to allow for hydrogen in utilities.	S2.8 Government
Economical change	S2.10 Enable electrolysis S2.11 & S2.12 Enable blue hydrogen S2.13 Shift from blue to green S2.14 Enable hydrogen infrastructure S2.15 & S2.16 Enable hydrogen in transport S2.17 Enable hydrogen in built environment	S2.10 Provide subsidies for electrolysis projects to ensure the business case. S2.11 Provide subsidies for blue hydrogen. S2.12 Provide subsidies for CCS extensions on existing SMR. S2.13 Stop subsidy schemes for blue hydrogen S2.14 Socialize costs of hydrogen infrastructure through spreading the costs over all grid connections. S2.15 Use fiscal incentives to facilitate hydrogen mobility. S2.16 Use subsidy schemes to facilitate hydrogen mobility. S2.17 Calculate costs in regions to determine the cheapest alternative heating system compared to natural gas.	S2.10 Government, RVO, electrolysis producers, electrolysis operators, investors. S2.11 Government, RVO, investors, SMR with CCS manufacturers. S2.12 Government, RVO, grey hydrogen producers. S2.13 Government S2.14 Government, DSO, TSO, hydrogen suppliers. S2.15 & S2.16 Government, lease companies, car owners, car resellers. S2.17 DSO, municipalities, governments.

6.3.3 Technical

The technical aspects of a vision consist of infrastructural change, production change, application change and R&D change. The technical changes of non-vision related findings are shown in Table 22.

In order to realize the goals of vision 2, changes to the infrastructure are needed. The infrastructure has to serve a growing demand and import should be enabled. Furthermore, the infrastructure will connect hydrogen with electricity. Current hydrogen production facilities are provided with carbon capture units to match the demand for hydrogen, but stay within climate goals. New production facilities are from the start blue hydrogen and on the long term will become green. For application, storage, heavy vehicles, high temperature heating and boilers need to be implemented. Research in vision 2 focusses on storage and heat in built environment.

Table 22 - Technical changes vision 2

	What	How	Who
Infrastructure	T2.1 Design hydrogen infrastructure T2.2 Design hydrogen clusters T2.3 Connect clusters T2.4 Enable hydrogen in transport T2.5 Design power balancing system	T2.1 Construct infrastructure in such a way different quality of hydrogen can be transported. T2.2 Create hydrogen clusters by construction of infrastructure that connects producers with users. T2.3 Construct infrastructure between clusters in case quality of hydrogen is similar. T2.4 Construct hydrogen refuelling infrastructure. T2.5 Use electrolysis as a conversion unit between electricity and hydrogen to integrate the grids.	T2.1 TSO, DSO, hydrogen suppliers. T2.2 Cluster regions, companies connected to cluster, TSO, DSO, hydrogen supplier. T2.3 DSO, TSO. T2.4 Local authorities, refuelling station builders, hydrogen transport companies. T2.5 TSO, utilities
Production	T2.6 Decrease grey hydrogen T2.7 Decrease blue hydrogen T2.8 Enable blue hydrogen	T2.6 Replace grey hydrogen production by blue hydrogen. T2.7 Replace blue hydrogen production by green hydrogen. T2.8 Construct carbon capture infrastructure.	T2.6 Grey hydrogen plant owners. T2.7 Electrolysis investors, hydrogen suppliers. T2.8 Infrastructure company
Application	T2.9 Design power balancing system T2.10 Allow for hydrogen storage T2.11 Enable hydrogen in industry	T2.9 Design flexible system around electrolysis to enable its flexibility. T2.10 Construct hydrogen storage facilities in salt caverns.	T2.9 Electrolysis chain investors and manufacturers. T2.10 TSO, Government, utilities, storage companies. T2.11 Industrial companies with high temperature

	T2.12 Enable hydrogen for HV	T2.11 Replace natural gas by hydrogen in industry for high temperature heating. T2.12 Develop HV hydrogen cars for mass transport.	heating, TSO, industrial clusters. T2.12 HV car companies.
R&D	T2.13 Development hydrogen in built environment T2.14 Development hydrogen storage	T2.13 Develop technology hydrogen heating further in built environment to proof safety, efficiency and scale potential. T2.14 Determine need for storage in salt caverns.	T2.13 DSO, boiler companies, housing corporation, municipalities. T2.14 TSO, Government, utilities, storage companies.

6.4 Findings vision 3

Changes described in this section relate to vision 3. First overall changes in culture will be discussed, then social changes and finally technical changes.

6.4.1 Cultural

The cultural aspects of a vision consist of behavioural change and educational change. The cultural changes of non-vision related findings are shown in Table 23.

Vision 3 is a vision where hydrogen is most important. Social acceptance of all the projects is very important. In order to gain support, demonstration projects for hydrogen in transport and built environment are used. Furthermore, behavioural change is seen in government bodies and companies. In order to have the most efficient transition towards hydrogen, well thought decisions have to be made.

Table 23 - Cultural changes vision 3

	What	How	Who
Behavioural change	C3.1 & C3.3 Social behaviour regarding environment and hydrogen	C3.1 Make decisions based on rational and not on social pressure of public by what solutions are technological feasible and cost efficient.	C3.1 Municipalities, government, DSO, TSO, public, companies involved in hydrogen projects and investment. C3.2 ACM, SODM, Ministry of EZK.

	C3.2 Enable hydrogen in built environment.	C3.2 Gain trust and support of regulating actors in built environment for hydrogen heating. C3.3 Shift focus of carbon reduction to reaching a circular bio-based energy system with a result carbon reduction by advertising on other strategy both politically as socially.	C3.3 Government, municipalities, industry, NGOs, environmental advisory groups
Educational change	C3.4 – C3.6 Knowledge on hydrogen technologies	C3.4 Design demonstration projects in built environment to show to public how heating of houses can be done with hydrogen. C3.5 Design demonstration projects with hydrogen for heavy vehicles with full supply chain. C3.6 Design demonstration projects with hydrogen for mobility purposes with refuelling stations and FCEV.	C3.4 DSO, municipality, residential area, home owners, boiler company, hydrogen producer, hydrogen distributer, housing corporation. C3.5 & C3.6 Car producers, hydrogen refuelling producers and operators, Heavy vehicle users, local/regional authority, ministry of infrastructure.

6.4.2 Structural

The structural aspects of a vision consist of institutional change, organisational change, legal change and economical change. The structural changes of non-vision related findings are shown in Table 24.

Hydrogen will play a large role in built environment, transport and industry in vision 3. All structural changes focus on support in sectors. Furthermore, legal changes are necessary to allow hydrogen as part of the public grid. The economic feasibility of hydrogen is supported by economical changes to guarantee business cases and fast implementation of hydrogen.

Table 24 - Structural changes vision 3

	What	How	Who
Institutional change	S3.1 Off the gas in built environment	S3.1 Stimulate approach in built environment to change 3% of	S3.1 DSO, TSO, municipalities, utilities, boiler

	S3.2 Import of hydrogen	households to other heat source than natural gas with up-to-date calculations. S3.2 Determine what sort of hydrogen (grey, blue and/or green) can be imported.	companies, house owners, housing corporations. S3.2 Government
Organisational	S3.3 Facilitate strong collaborations	S3.3 Enable support to invest in hydrogen infrastructure of the future by taking risk away.	S3.3 Government, DSO, TSO, hydrogen suppliers.
Legal change	S3.4 - S3.6 Hydrogen to public grid	S3.4 Include hydrogen in Gas Law to allow grid operators to transport hydrogen in public gas infrastructure. S3.5 Define hydrogen infrastructure as a public grid with regulatory framework as for natural gas. S3.6 Legally facility third party access in hydrogen grid.	S3.4 Government S3.5 & S3.6 Government, DSO, TSO, hydrogen suppliers.
Economical change	S3.7 & S3.8 Enable blue hydrogen S3.9 Enable hydrogen infrastructure S3.10 & S3.11 Enable hydrogen in transport	S3.7 Provide subsidies for blue hydrogen. S3.8 Provide subsidies for CCS extensions on existing SMR. S3.9 Socialize costs of hydrogen infrastructure through spreading the costs over all grid connections. S3.10 Use fiscal incentives to facilitate hydrogen mobility. S3.11 Use subsidy schemes to facilitate hydrogen mobility.	S3.7 Government, RVO, investors, SMR with CCS manufacturers. S3.8 Government, RVO, grey hydrogen producers. S3.9 Government, DSO, TSO, hydrogen suppliers. S3.10 & S3.11 Government, lease companies, car owners, car resellers.

6.4.3 Technical

The technical aspects of a vision consist of infrastructural change, production change, application change and R&D change. The technical changes of non-vision related findings are shown in Table 25.

In order to realize the goals of vision 3, large infrastructural changes are needed. The infrastructure has to serve the three sectors and import should be enabled. To match the demand for hydrogen, but stay within climate goals, current hydrogen production facilities are provided with carbon capture units. New production facilities are from the start blue hydrogen. Furthermore, construction in all the sectors is needed to guarantee the demand. Research in vision 3 focuses on how to integrate the different sectors and how to optimize the infrastructure. Scale in each sector with hydrogen is a challenge that R&D can provide guidance in.

Table 25 - Technical changes vision 3

	What	How	Who
Infrastructure	T3.1 Design hydrogen infrastructure T3.2 Design hydrogen clusters T3.3 Connect clusters T3.4 Design international infrastructure T3.5 Enable hydrogen in transport T3.6 Enable hydrogen in built environment	T3.1 Construct infrastructure in such a way different quality of hydrogen can be transported. T3.2 Create hydrogen clusters by construction of infrastructure that connects producers with users. T3.3 Construct infrastructure between clusters in case quality of hydrogen is similar. T3.4 Construct hydrogen infrastructure between countries T3.5 Construct hydrogen refuelling infrastructure T3.6 Construct hydrogen infrastructure for built environment	T3.1 TSO, DSO, hydrogen suppliers. T3.2 Cluster regions, companies connected to cluster, TSO, DSO, hydrogen supplier. T3.3 DSO, TSO. T3.4 TSO, Dutch neighboring countries T3.5 Refueling operator, TSO, DSO, hydrogen operator T3.6 DSO, municipalities, home owners, housing corporations
Production	T3.7 – T3.8 Enable blue hydrogen	T3.7 Replace grey hydrogen production by blue hydrogen.	T3.7 Grey hydrogen plant owners. T3.8 Infrastructure company

		T3.8 Construct carbon capture infrastructure. T3.9 Construct blue hydrogen production	T3.9 CCS manufacturers, and grey hydrogen manufacturers
Application	T3.10 Enable hydrogen in industry T3.11 Enable hydrogen in built environment T3.12 & T3.13 Enable hydrogen in transport	T3.10 Replace natural gas by hydrogen in industry for high temperature heating. T3.11 Manufacture boilers for built environment T3.12 Manufacture hydrogen vehicles T3.13 Manufacture hydrogen boats	T3.10 Industrial companies with high temperature heating, TSO, industrial clusters. T3.11 Boiler manufacturers T3.12 Car and truck manufacturers T3.13 Shipyards
R&D	T3.14 Development hydrogen in transport T3.15 Development hydrogen in built environment T3.16 Development on hydrogen integration T3.17 Development hydrogen infrastructure	T3.14 Research on scaling of transport T3.15 Research on scaling of hydrogen in built environment T3.16 Research on integration of several sectors in hydrogen economy T3.17 Research hydrogen infrastructure, what it should look like.	T3.14 – T3.17 TSO, DSO Government, sector specific companies, research institutes, universities.

6.5 Drivers for hydrogen

In this section, drivers for hydrogen are discussed. Drivers for hydrogen have been aggregated according to the results of the interviews. The following drivers have been often mentioned in interviews:

1. Increase for RES asks for power balancing with alternative energy carriers and storage (in 7 interviews).
2. Decrease of natural gas supply and demand offers opportunity to use natural gas grid (in 4 interviews).

3. Transport and storage of electrons is expensive and inefficient while molecules are easier, cheaper and more efficient (in 5 interviews).
4. Electrolysis has quick reaction times what offers opportunities for flexibility (in 2 interviews).
5. Decarbonization of industry and realising a circular bio-based economy (in 6 interviews).

First, renewable energy is becoming cheaper and more competitive. Furthermore, the Netherlands has large offshore wind potential. With increasing renewable energy, power balancing becomes more challenging, due to RES intermittent nature. The surplus of renewable energy can be converted and stored to cover seasonal fluctuations. Hydrogen is often mentioned as the key in connecting electrons with molecules.

Second, production and usage of natural gas has to decrease in the Netherlands due to earthquakes in Groningen. Therefore, a momentum for natural gas alternatives is initiated including hydrogen. The natural gas infrastructure will be used less. With small adjustments the natural gas infrastructure can be transformed to a hydrogen infrastructure.

Third, transportation of electricity is difficult and expensive. Capacity of electricity grid is reaching its maximum with increasing RES. The losses are very high when electricity is transported over long distances. Gasses are often cheaper to transport, and losses are limited. The capacity of gas infrastructure is much larger than that of electricity. Therefore, using hydrogen as energy carrier to transport and store energy is an interesting alternative to expanding electricity grid.

Fourth, electrolysis is a flexible technology with quick ramping up and down time. When the system is designed for flexibility, electrolysis can be used efficiently for power balancing and extracting electricity from the electricity grid.

Fifth, the Netherlands has a large chemical industry that has a large demand for electricity and fossil fuels. For some applications, electricity is not sufficient. Hydrogen is seen as an energy carrier to decarbonize the industry. Furthermore, hydrogen enables a circular bio-based economy where hydrogen can be seen as a building block. Hydrogen capture carbon emissions to produce new products that can be used elsewhere. The industry has experience with hydrogen, since it is already used as feedstock and an infrastructure is in place.

6.6 Barriers for visions

In this section, barriers for hydrogen are discussed. barriers for hydrogen have been aggregated according to the results of the interviews. The following barriers have been often mentioned in interviews:

1. Law and regulation hydrogen in public grid (in 3 interviews)
2. Costs for electrolysis and CCS (in 3 interviews)
3. Costs infrastructure (in 3 interviews)
4. Investment uncertainty hydrogen projects, infrastructure and market development (in 4 interviews)
5. Transport and storage of hydrogen (in 5 interviews)
6. Technological limitations and scaling of blue and green hydrogen (in 3 interviews)
7. Social acceptability and societal costs (in 3 interviews)

First, hydrogen is currently not seen as a utility. The existing infrastructure is privately operated. DSOs and TSOs are limited by law to operate hydrogen in the natural gas grid and to construct hydrogen infrastructure. In case regulations are made for industry towards sustainable production of hydrogen and increasing costs of hydrogen, there is chance of carbon leakage; companies that move their operations to other locations.

Second, high costs are related to hydrogen. Electrolysis is not competitive with current hydrogen costs. Though due to scaling effects the costs for electrolysis will go down. Furthermore, green hydrogen costs depend on electricity prices and those are currently too high to compete with grey hydrogen. In case scale for electrolysis and hydrogen in certain sectors is not reached, the costs will stay relatively high and electrolysis is not cost effective. Blue hydrogen has additional costs for the carbon capture unit and infrastructure for carbon. Both green and blue hydrogen are without support not cost competitive. A risk that may occur, in case blue hydrogen becomes cost competitive, electrolysis will have an additional barrier to become cost effective with subsidized blue hydrogen plants.

Third, long-term investment risks occur for infrastructure. Infrastructure investments are done for a long time. Return on investment periods are often long. Without scale for hydrogen, investment costs in infrastructure are very high.

Fourth, high investment uncertainty is related to the cost uncertainty. Many factors cannot be predicted especially due to the long timespan of projects and the uncertainty whether hydrogen will have scale in the time of project realisation. Company agendas are often made for many years ahead, while the political agenda can change every new political climate.

Fifth, while storage and transport of hydrogen theoretically is possible, the challenge lies in realising the capacity. Storage in salt caverns is limited to availability with potential need for expansion to other countries what increases costs. Other transport means such as trailer transport is less efficient than fossil fuel transport via truck. When importing hydrogen, costs for an international grid may be very high and there is a risk related to political unstable regions.

Sixth, green and blue hydrogen have some technical limitations. Electrolysis has a shorter life span than SMR and is more sensitive to failure due to impurities in water. Furthermore, scaling of electrolysis is challenging since the current electrolysis plants cover around 10 MW, while in future projects 1 GW electrolysis plants are discussed. SMR with CCS is not effective when hydrogen is used to capture carbon, what leads to an inefficient process. When blue hydrogen is seen as a transition process, large investments in carbon infrastructure are done, while the infrastructure has a short lifespan.

Seventh, while hydrogen offers a similar customer experience as the current energy system, social acceptability forms a barrier. In case in pilot projects accidents occur, the public might go averse to hydrogen. Furthermore, the public opinion is slightly against gasses underground after the situation in Groningen.

6.7 Diversity in interviews

The results of this chapter a gathering of results of the interviews. During the interviews some confliction opinions of experts and stakeholders have been addressed. Large differences were found during the interviews are (1) the position of blue hydrogen, (2) carbon leakage, (3) the role of hydrogen in transport and built environment, and (4) infrastructure design. Each conflicting element is explained with its argumentation.

First questions on the position of blue hydrogen leads to conflicting results in interviews. On one side a few interviewees argue that blue hydrogen is necessary to create scale for a growing hydrogen demand. Green hydrogen production has not yet reached over a GW of capacity in the Netherlands, while SMR technology is commonly used for hydrogen production. Blue hydrogen offers an easier transition of SMR to less emissions with a carbon capture unit. Costs of replacement are larger than an electrolysis unit. On the other side, interviewees argue supporting blue hydrogen for transition demands a carbon capture infrastructure for a limited period of time. Large investments are necessary for a carbon capture infrastructure.

Furthermore, when blue hydrogen is politically supported, this may lead to very subsidized blue hydrogen facilities. It will become more difficult for green hydrogen to become competitive with blue hydrogen. Hydrogen can be used to utilize carbon for new products. In case blue hydrogen is used for this process, at the end of the balance there is still carbon capture necessary, because carbon for hydrogen production is captured.

Second, a debate can be seen on the influence of carbon leakage and how to handle it. Often, as a response to strict regulations and increasing carbon taxes, carbon leakage may occur in industry. On one side, interviewees argue that no strict regulations should be on place on industry when it comes to hydrogen production. It is even questioned whether carbon leakage would be bad from a Dutch climate goal perspective. On the other side, interviewees mention opportunities where hydrogen can play a role in enabling circular bio-based supply chains. Green hydrogen can play a role in linking several industries to each other and increase dependency between industrial actors. With stronger co-dependency, companies will not move their core business to another country. The challenge to avoid carbon leakage is to increase co-dependency and make companies in the most efficient, innovative technologies within Dutch boarders.

Third, the role of hydrogen in transport and built environment leads to a variety of opinions. Some see large potential for hydrogen in both industries, while some are more critical on implementation. For example, over the last couple of years electric vehicles have been supported. The question is raised whether hydrogen vehicles should enter this market. In addition, the role of hydrogen in the built environment is by some not even mentioned. Alternatives show at this point more potential than hydrogen. Interviewees that do believe in hydrogen for built environment, have different levels of implementation varying between only for peak demand and seasonal fluctuations, to entire regions on hydrogen.

Fourth difference is the design of the future hydrogen infrastructure. At this point a hydrogen infrastructure is in place with a certain hydrogen quality to serve (petro)chemical industry and ammonia industry. Several actors argue for a central infrastructure, first starting in industrial clusters and expanding by connecting the clusters. Critique on the central infrastructure approach is the fact that for different applications different qualities of hydrogen are necessary. A central infrastructure may not serve all hydrogen users. An infrastructure with the best quality of hydrogen may become expensive and with the worst quality may push up prices of better qualities. Besides the central approach, in some interviews multiple infrastructures where issued. The demand per sector differs strongly, same as the required quality of hydrogen.

Multiple infrastructures for several hydrogen qualities could be designed where even a combination of public and private, a hybrid, infrastructure could be in place.

6.8 Conclusion Backcasting

For each vision backcasting elements have been identified. Some elements are relevant for each of the visons, while some are vision specific. For vision 1, the vision specific elements include development of hydrogen in the electricity sector for power balancing and transforming the current hydrogen sector to green hydrogen production. For vision 2, the vision specific elements include on one side hydrogen in the electricity sector and on the other side hydrogen in various sectors for end use. Public support of hydrogen becomes more important. For vision 3, the vision specific elements include the roll out of hydrogen in all possible sectors for end use. All changes made are in service of scaling hydrogen.

The drivers and barriers for hydrogen are discussed, though not assigned to specific visions. The drivers and barriers strongly influence the outcome of the pathway. Furthermore, differences in perspective between the interviewees are summarized. The differences are (1) the position of blue hydrogen, (2) carbon leakage, (3) the role of hydrogen in transport and built environment, and (4) infrastructure design.

To conclude, the identified changes with backcasting and the four differences in views on hydrogen in the Netherlands strongly influence the pathways and roadmaps for hydrogen.

7 Pathways & roadmapping

Chapter 7 describes the pathways and roadmaps for each vision. First, the basis for each pathway is discussed for each vision, before the visions are further explained separately in 7.1 Vision 1, 7.2 Vision 2 and 7.3 Vision 3. Every vision section first elaborates on the pathway of hydrogen integration in the energy system. After that the roadmap is shown. From the roadmap key changes can be identified that form the basis for identifying the key stakeholders. For each key stakeholder the effect of the vision, actions and motivation are identified. Finally, bottlenecks per vision are selected with policy measures to overcome them. The chapter is concluded with comparison of vision pathways and roadmap with indicators on differences in pathways, costs and implementation of technology.

During the interviews, questions have been asked how to realize the visions. The answers have been coded and the results have led to a list of pathway principles. The pathway principles relate to the differences found between opinions of interviewees (section 7.4). Opinions have been included to the visions with pathway principles as shown in Table 26.

Table 26 - Visions with the basis for their pathway and roadmap

	Pathway principles of interviews
Vision 1 – All Electric	Use hydrogen for flexibility. Make current system fully green. Do not use blue hydrogen as intermediate. Scale electrolysis is created along growth of offshore wind capacity. Infrastructure plans included in offshore wind projects.
Vision 2 – One integrated system	Use hydrogen for flexibility. Use hydrogen in built environment as intermediate solutions while improving energy efficiency. Blue hydrogen is used to create scale with clear boundaries. Facilitate transition of blue hydrogen to green hydrogen. Create scale in hydrogen with industry.
Vision 3 – Go hydrogen	Adjust built environment with 3% a year with hydrogen in the mix. Blue hydrogen for scale and for support of green hydrogen. Create scale with industry. Include other sectors in industry projects simultaneous. Plan infrastructure for the future capacity to cover future demand. Invest in a global hydrogen market.

7.1 Vision 1

As described in 5.2.1 Vision 1: All Electric the first vision focusses on an all-electric system. Hydrogen is used as a flexibility measure for electricity. Hydrogen, also for current hydrogen demand, is produced from electrolysis. As shown in Table 26, the pathway of Vision 1 is based on a system with a large capacity of RES with a high level of electrification. The large share of RES demands flexibility measures. Hydrogen production, i.e. electrolysis, will grow simultaneous with the growing capacity of offshore wind (Figure 26). Efficiency improvements have been taken into consideration varying by 2050 between 74 – 81% (IEA, 2019; Waterstof Coalitie, 2018). Since hydrogen is used as a secondary energy carrier in the energy system, only green hydrogen is implemented. By the time a larger capacity of electrolysis is installed, current SMR facilities are replaced by the electrolysis. The demand for hydrogen in industry will stay constant, while the demand for power balancing increases with growing capacity of RES (Figure 27).

How to get to an all-electric system, a backcasting study has been conducted. The found changes in the study have been categorized and allocated in time. The backcasting elements for vision 2 can be found in section 6.1 & 6.2. Table 27 is the roadmap for hydrogen in vision 1. Three phases have been identified. In the development phase wind is scaled and electrolysis technology is further developed. The scale-up phase is the period where electrolysis can be scaled -up to fast growing levels per year.

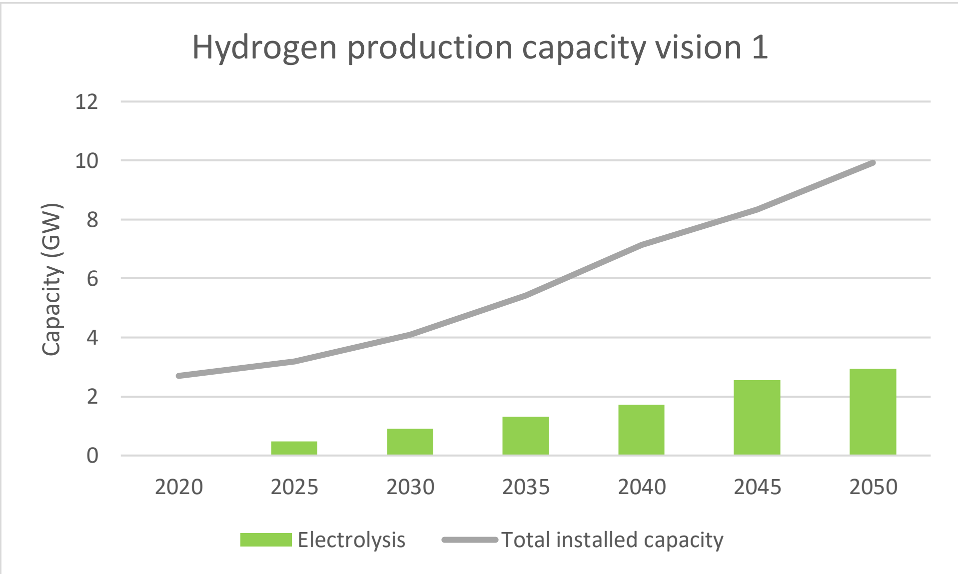

Figure 26 - Hydrogen production capacity growth and total installed from 2020-2050 for vision 1.

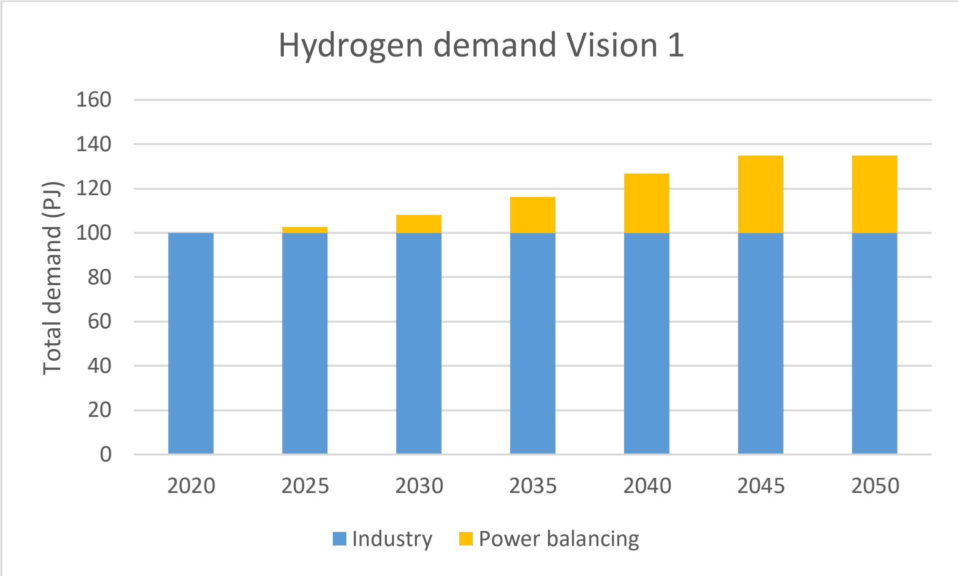

Figure 27 - Hydrogen demand per sectors between 2020 and 2050 for vision 1.

Gas fired power plants are reconstructed for hydrogen and first infrastructure for hydrogen is built. After scale-up phase, the maturation phase is reached. In this phase electrolysis is well developed and the market matured. Still the electrolysis capacity grows quickly, but with consistent prices and technology.

From the roadmap key changes to the system can be identified. The key changes to the system for vision 1 are:

- Growth of offshore wind capacity and electrification over time
- Replacing current hydrogen production of SMR with electrolysis
- Electrolysis capacity for balancing the electricity grid (Power-to-H2)
- Storage of hydrogen in salt caverns
- Electricity generation in gas fired plants with hydrogen (H2-to-Power)
- Infrastructure for hydrogen between offshore wind, electrolysis, storage facilities and hydrogen power plants.

The changes are mostly executed by four actors in the system, i.e. utilities, TSO, electrolysis manufacturers and current hydrogen producers. The key actors have been identified during interviews where with several actors and potential actors the role of various stakeholders is discussed in more detail. Elements of the reports selected for vision comparison are also taken into consideration when selecting the key actors for vision 1. The key actors are strongly influenced by vision 1 and may accordingly behave in a certain way to change the current system (Table 28).

Table 27 - Roadmap vision 1

		Development	Scale-up		Maturation	
		2019-2025	**2025-2030**	**2030-2035**	**2035-2040**	**2040-2050**
Cultural	*Behavioural*		Corporate support H2 in utilities	Acceptance hydrogen underground Industry focus on green		
	Educational	Research programs hydrogen	Educate on electrolysis construction and operation Demonstration programs hydrogen			
Structural	*Institutional*	Determine preconditions tenders &subsidies hydrogen	Tenders for wind with hydrogen	Tenders electrolysis financial support Tenders storage in salt caverns Determine quality hydrogen infrastructure	Determine property rights hydrogen infrastructure Tenders electrolysis no financial support	
	Organisational	KPIs Leadership government	Company agendas for next 20-30 years Create collaborations with MVC			
	Legal	Divide risk in projects	Regulations on grey hydrogen productions Set contracts actors hydrogen projects	Regulations and conditions on hydrogen in power sector on safety and efficiency	Regulations on hydrogen in power plants	
	Economic	Determine long investment plan infra hydrogen		Subsidy on circular bio-based industry Subsidy electrolysis Taxes on SMR		
Technical	*Infrastructure*		Hydrogen infra to match supply & demand	Design infra for future demand (up to 2050)	Link hydrogen infrastructure with electricity infra Natural gas infra to hydrogen	
	Production	Find efficient materials for electrolysis	Industrialize production of electrolysis Redesign supply chain electrolysis	Built electrolysis capacity	Scale electrolysis	Replace grey production hydrogen to green production
	Market		Short term storage hydrogen Design system electrolysis for flexibility purpose	Focus on circular bio-based industry Enable multiple energy carriers Construct hydrogen power plants	Hydrogen and carbon for new products in industry Scale hydrogen power plants	Construct hydrogen in salt caverns Cross boarder storage Store surplus electricity in hydrogen
	R&D	Monitor technologies Research on electrolysis Research on Power plants with hydrogen	Research on storage in salt caverns Research natural gas grid to hydrogen	Determine need salt caverns		

Table 28 - Influence of vision 1 of key actors

Actor	How is the actor affected by vision 1?	What action should the actor take to change the current system accordingly?	What may be the motivation behind the change?
Utilities	Fluctuations; business case with storage; hydrogen powerplants	Start including electrolysis in business cases offshore wind; Facilitate storage for hydrogen; Built hydrogen power plants for peak demand	New opportunities and business cases. Surplus of electricity that may be used in a more efficient way. As long as natural gas is cheaper in gas fired power plants, hydrogen will not be used.
Tennet & Gasunie	Pressure electricity grid; new potential grid for Gasunie; storage hydrogen needed	Expand electricity grid; lobby for storage; Gasunie may become involved in hydrogen infrastructure	Provide grid of the future; new opportunities; Gasunie: smaller market for natural gas with large gas infrastructure.
Electrolysis manufacturer	Large demand electrolysis; need for flexible hydrogen system	Expand electrolysis manufacturing capacity; improve efficiency electrolysis; professionalize production process for scaling	Business opportunities; serve bigger market; become market leader
Current hydrogen producers	Green hydrogen production; Green hydrogen production; potential involvement hydrogen infrastructure.	Replace SMR capacity with electrolysis; get involved in hydrogen projects for infrastructure	Emission reduction; new opportunities and business cases; motivation to shift from SMR to electrolysis must be or for economic consideration or to match increasing regulations on emissions.

The key actors will enable vision 1 with the actions they take. Collaboration and interaction take place between the actors. Though, the government has a key role in facilitating adjustments to the system. While utilities find new business cases in electrolysis inclusion in offshore wind projects, they will have to collaborate with other parties and even find support to scale hydrogen production. The government has two possible pathways to position themselves. First, they can take a lead and respond to problems that may occur in the evolving system with an increase of renewables and electrification. Second, they can take a leadership role and guide key actors in the needed changes for vision 1. In both situations, the government will set clear goals for 2050 with especially offshore wind on the agenda. Electrolysis will become an important technology of the current regime.

Actions the government can take link to bottlenecks that cause tension between the current system and vision 1. The bottlenecks have been identified during the interviews as form of barriers as discussed in section 6.6 and the solutions have been elaborated on in the backcasting questions. While actors will have certain drivers for change, policy measures are still necessary to realize the vision. The most important bottlenecks for vision 1 are costs of electrolysis, costs of green hydrogen, scale electrolysis and infrastructure for electrolysis (Table 29). Investments in power plants could be seen as a risk, though it is known prices will fluctuate more and there is a large demand for baseload.

Table 29 - Vision 1 bottlenecks and policies

Bottleneck	**What needs to be done**	**Policy**
Costs electrolysis	Production cost reduction Reduction CAPEX	Subsidies for production improvements; tenders
Competitiveness green hydrogen	Reduce cost electricity Increase costs natural gas Improve efficiency	Provide feed-in tariff hydrogen; provide carbon tax; subsidies for improvements; regulations on grey hydrogen
Scale electrolysis	Professionalization electrolysis manufacturing Stimulate electrolysis capacity Decrease attractiveness SMR	Subsidy and regulations Tenders for capacity and set preconditions Strict conditions on emissions hydrogen production
Infrastructure hydrogen	Determine regulatory framework infrastructure Provide funds infrastructure	Define regulatory framework; provide tenders for hydrogen; include hydrogen infrastructure guarantee in tenders

7.2 Vision 2

As described in 0

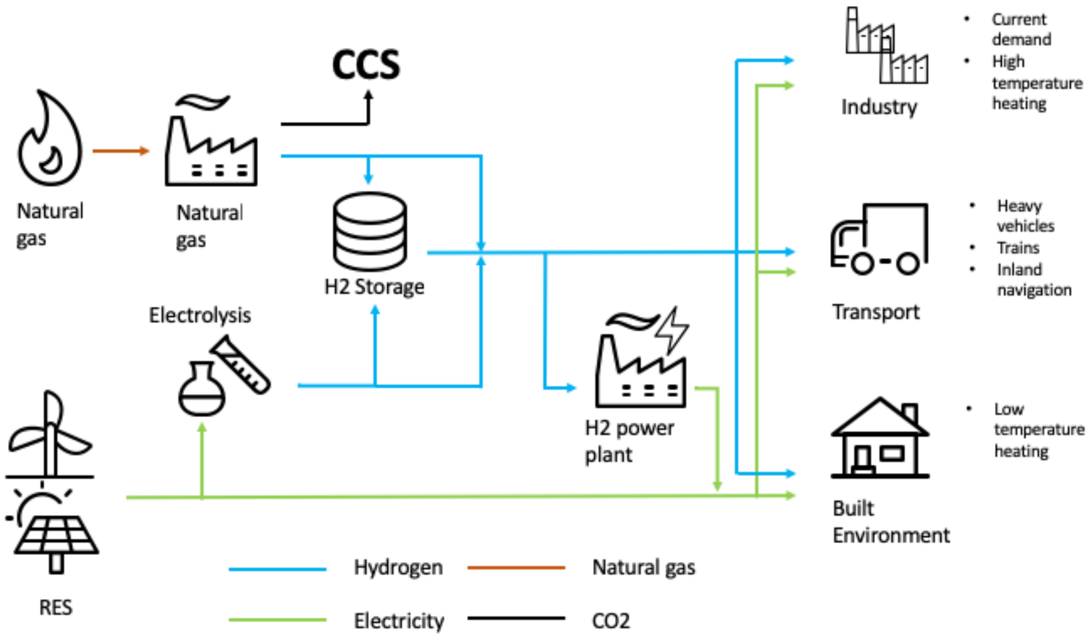

Figure 24 - System diagram of vision 2: One integrated system

Vision 2: One integrated system the second vision describes a system where electricity and hydrogen are combined energy carriers. Hydrogen is used in situations where it works better than electricity. For the markets this means hydrogen is used for high temperature heat in industry, as heat source in built environment, and as fuel for heavy transport. Similar to vision 1, hydrogen is also used for storage in the power sector. As shown in Table 26, the pathway of Vision 2 is based on integration of hydrogen as primary energy carrier (in built environment, industry and transport) and as secondary energy carrier (in power balancing). An integrated energy system with both electricity and hydrogen is constructed (Figure 28). Efficiency improvements have been taken into consideration varying by 2050 between 80 – 81% (Agora Verkehrswende, Agora Energiewende, & Frontier Economics, 2018; Waterstof Coalitie, 2018). In order to scale the hydrogen demand, blue hydrogen is used to provide early increase in demand. Simultaneously, electrolysis is further developed and scaled over time. By the time electrolysis is competitive, existing SMR capacity is removed and replaced by electrolysis. For demand, while hydrogen in industry and transport is seen as a long-term solution to decarbonize the sectors, in case of the built environment hydrogen is seen as a transition solution (Figure 29).

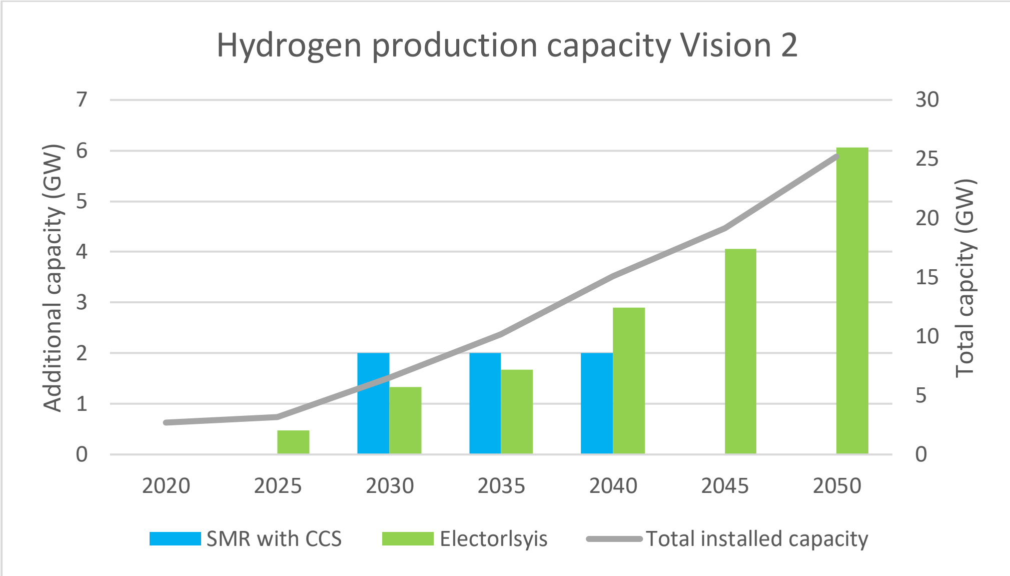

Figure 28 - Hydrogen production capacity growth and total installed from 2020-2050 for vision 2.

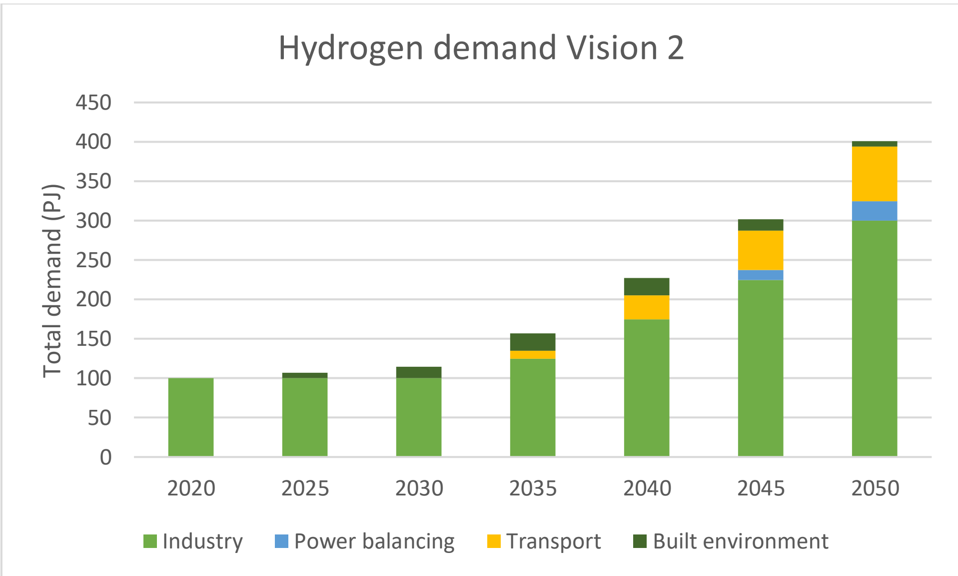

Figure 29 - Hydrogen demand per sectors between 2020 and 2050 for vision 2.

In early stages, hydrogen is promoted along improving energy efficiency overtime. By the time the hydrogen boilers need replacement, alternative heating solution will be more suitable and can be replaced by another heat solution. Therefore, in the time period between 2020 and 2050 the demand for hydrogen in built environment will increase and decrease.

To determine how vision 2 could be realised, a backcasting study is conducted and the changes are allocated to time. The backcasting elements for vision 2 can be found in section 6.1 & 6.3. Table 30 is the roadmap for hydrogen in vision 2. Three phases in the roadmap have been identified, i.e. development, scale-up hydrogen, scale-up green. The development phase entails further research and development on hydrogen and first facilitation of investments in hydrogen projects. The scale-up hydrogen phases focus on implementing hydrogen applications. The first projects for electrolysis are started, but blue hydrogen is also supported. Hydrogen is promoted in built environment, industry, heavy vehicles and storage. In the built environment simultaneously, insulation measures to buildings are still promoted. The scale-up green phase shifts focus on scaling hydrogen to making hydrogen green. Blue hydrogen plants are replaced by electrolysis and electrolysis is further scaled. In addition, insulation measures in buildings increase and other technologies than hydrogen can be used for heating. The first hydrogen heating boilers are replaced by alternatives.

Table 30 - Roadmap vision 2

		Development	**Scale-up hydrogen**		**Scale-up green**	
		2019-2025	**2025-2030**	**2030-2035**	**2035-2040**	**2040-2050**
Cultural	*Behavioural*	Social acceptance hydrogen underground Incorporate hydrogen in wind projects Corporate support on hydrogen	Critical on hydrogen Gain trust and support of regulating actors in built environment	Improve insulation households Stimulate current hydrogen industry to go green	Circular bio-based industry	
	Educational	Set research programs hydrogen Demonstration hydrogen in built environment	Educate on construction and implementation hydrogen	Demonstration hydrogen in transport sector		
Structural	*Institutional*	Divide risks commitments	Wind with hydrogen tenders Company agendas for 20-30 years Stimulate companies to invest in Netherlands	Determine quality hydrogen in infrastructure Tenders for electrolyse Determine on import hydrogen	Enable storage in salt caverns	
	Organisational	Set KPIs Governmental leadership Collaborations with MVC Hydrogen investment plan				
	Legal	Regulate on safety and efficient hydrogen in built Contracts projects	Design stricter regulations for grey hydrogen Regulation on CCS	Regulate hydrogen in utilities Align NL & EU regulations	Define hydrogen infrastructure: public or private	
	Economic	Cheapest solution in built environment Long term investment plan infrastructure	Subsidize CCS in SMR Subsidize blue hydrogen Socialize costs infrastructure	Subsidize electrolysis Stop subsidy on blue hydrogen Subsidize circular bio-based	Increase carbon tax Fiscal incentives transport sector Subsidize transport sector	
Technical	*Infrastructure*	Create hydrogen clusters (match producers with users) Design infrastructure for different purpose	Design CCS infrastructure Design infrastructure hydrogen for future Natural gas grid to hydrogen	Construct hydrogen refuelling infrastructure	Use electrolysis to link hydrogen with electricity infrastructure	Design infra between clusters
	Production	Construct small electrolysis capacity	Grey to blue hydrogen Find efficient materials for electrolysis	Industrialize production of electrolysis Design flexible system electrolysis	Scale electrolysis	Blue to green hydrogen
	Market	Short term storage	Hydrogen for built environment	Hydrogen for high temperature Redesign gas fired plants for hydrogen Implement heavy vehicles in transport	Construct storage in salt caverns hydrogen Integrate hydrogen for flexibility electricity Implement ships on hydrogen	Scale hydrogen in transport Replace hydrogen heating system in built environment Construct cross boarder storage
	R&D	Monitor technologies Research hydrogen in built environment Research natural gas grid to hydrogen	Research electrolysis Research hydrogen in salt caverns Research hydrogen in heavy vehicles	Research hydrogen in inland navigation		

From the roadmap key changes to the system can be identified. The key changes to the system for vision 2 are:

- Provide hydrogen production with green and blue hydrogen
- Start with blue hydrogen and move it to green on long term
- Start with hydrogen in built, keep improving efficiency in built, replace hydrogen with electricity etc when well insulated
- Replace natural gas by hydrogen for > 500 degrees Celsius in industry
- Implement hydrogen in heavy vehicles and inland navigation
- Enable hydrogen infrastructure that supports hydrogen in built environment, increasing demand in industry and hydrogen for transport with refuelling infrastructure.

The changes are mostly executed by four actors in the system, i.e. TSO, DSO, current hydrogen producers and utilities. The key actors have been identified during interviews where with several actors and potential actors the role of various stakeholders is discussed in more detail. Elements of the reports selected for vision comparison are also taken into consideration when selecting the key actors for vision 2. The key actors are strongly influenced by vision 2 and will accordingly behave in a certain way to change the current system (Table 31).

The key actors will enable vision 2 with the actions they take. To realize large scale projects, collaboration between the key actors is necessary. The government can influence the actions actor take by policy and regulations. Vision 2 has applications of hydrogen emerging that are new. Without support of the government, vision 2 cannot be realized, because new technologies will not become competitive. Collaboration between government and involved actors is crucial to overcome the challenges. For vision 2 two pathways are possible. The first pathway is where the government takes leadership and determines on the new developments to be implemented. In the other pathway companies drive the change. They will ask the government for support in order to realize the development of hydrogen. The first pathway will provide more security for investments, because the direction of hydrogen is clearer.

Table 31 - Key actors vision 2

Actor	How is the actor affected by vision 1?	What action should the actor take to change the current system accordingly?	What may the motivation behind the change?
Tennet & Gasunie	Increase in demand for Power-to-hydrogen; need for natural gas grid; energy storage solution	Investing in hydrogen grid; lobby for storage; facilitate hydrogen storage; new core business potential for Gasunie	Provide grid of the future; new opportunities
DSOs	Demand for hydrogen in built environment; potential hydrogen in natural gas infrastructure	Facilitate hydrogen infrastructure to households where necessary; Chose locations with good connections to high demand areas for hydrogen; transform natural gas grid; chose technical applications with lowest social impact	Provide low carbon alternative heating source; alternative use for natural gas gird
Current hydrogen industry	Current SMR provided with CCS; blue hydrogen to green hydrogen; potential new markets with growing demand hydrogen	Include CCS to SMR units; Replace CCS units to electrolysis; expand infrastructure; gain new customers; start collaborations with high temperature industry	Business opportunities; emission reductions; matching regulations
Utilities	Growing energy capacity; hydrogen in offshore wind projects; electricity production with hydrogen fired power plants	Include electrolysis for offshore; start building additional offshore wind capacity solely for hydrogen production; facilitate storage for hydrogen; built hydrogen power plants	New business opportunities; response to demand

In both pathways the actions of the government will enable to overcome bottlenecks for vision 2. Without support, companies might not be able to realize the change and perform the proposed actions. The bottlenecks have been identified during the interviews as form of barriers as discussed in section 6.6 and the solutions have been elaborated on in the backcasting questions. While actors will have certain drivers for change, policy measures are still necessary to realize the vision. The most important bottlenecks for vision 2 are the cost of electrolysis, competitiveness of green hydrogen, competitiveness of blue hydrogen, competitiveness of hydrogen vehicles and costs in built environment. Table 32 shows the bottlenecks and policy measures for vision 2.

Table 32 - Vision 2 bottlenecks and policies

Bottleneck	What needs to be done	Policy
Costs electrolysis	Production cost reduction Reduction CAPEX	Subsidies for production improvements; tenders
Competitiveness green hydrogen	Reduce cost electricity Increase costs natural gas Improve efficiency	Provide feed-in tariff hydrogen; provide carbon tax; subsidies for improvements
Competitiveness blue hydrogen	Increase cost emissions	Regulations on grey hydrogen; provide carbon tax; provide feed-in tariff
Competitiveness hydrogen vehicles	Increase costs fossil fuels	Provide carbon tax; increase regulations on fossil fuel vehicles; subsidies/tenders for refuelling infrastructure
Costs built environment	Production costs boilers Scale boilers Increase costs fossil fuels Reduce costs hydrogen grid connections	Subsidies improvement production; tenders for boilers; socialize costs; provide carbon tax on natural gas in built environment
Infrastructure hydrogen	Determine regulatory framework infrastructure Provide funds infrastructure	Define regulatory framework; provide tenders for hydrogen; include hydrogen infrastructure guarantee in tenders

7.3 Vision 3

As described in

Vision 3: Go Hydrogen the third vision focusses on a system with a large share of hydrogen. The application of hydrogen as primary energy source is strongly supported by the government. The idea behind the vision is to create fast a hydrogen market. Demand for hydrogen is expected in industry, built environment and mobility. To match the demand, green and blue hydrogen production is combined, and hydrogen is imported. Scale in production to match the increasing demand is done with blue hydrogen (Figure 30). Efficiency improvements have been taken into consideration varying by 2050 between 80 –82% (Agora Verkehrswende et al., 2018; Waterstof

Coalitie, 2018)After 2030, electrolysis technology has matured and is ready to scale to match the increasing demand of hydrogen.

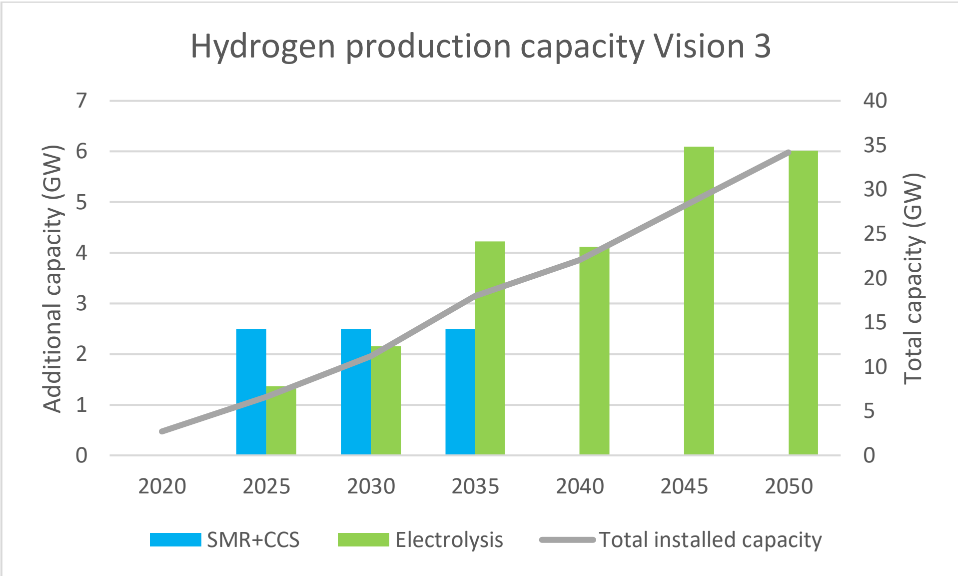

Figure 30 - Hydrogen production capacity growth and total installed from 2020-2050 for vision 3.

Though the demand is still large, and a European hydrogen market has been developing. A hydrogen pipeline connection is made between the Netherlands and neighbouring countries for import of hydrogen. The demand for hydrogen starts with industry (Figure 31). From industry other sectors are explored. In built environment a steady pace of replace natural gas by alternative heating sources takes place. Hydrogen is implemented for low insulated buildings and to cover peak demand in district heating. Hydrogen demand in transport increases with market readiness of hydrogen vehicles over time. The infrastructure for hydrogen is built in the early 20s in order to facilitate a growing supply and demand.

How to get to an all hydrogen system, a backcasting study has been conducted. The found changes in the study have been categorized and allocated in time. The backcasting elements for vision 2 can be found in section 6.1 & 0. Table 33 is the roadmap for hydrogen in vision 3. Three phases have been identified. The development phase focusses on further development of hydrogen technologies. The development is necessary to start scaling to large hydrogen demand. Hydrogen will be implanted in built environment and passenger transport and therefore social support is necessary. The development phase allows for demonstration projects to gain public support. The scale-up phase is the phase demand and supply are quickly growing. Simultaneously the infrastructure will be constructed. The plans for infrastructure are made in the development phase.

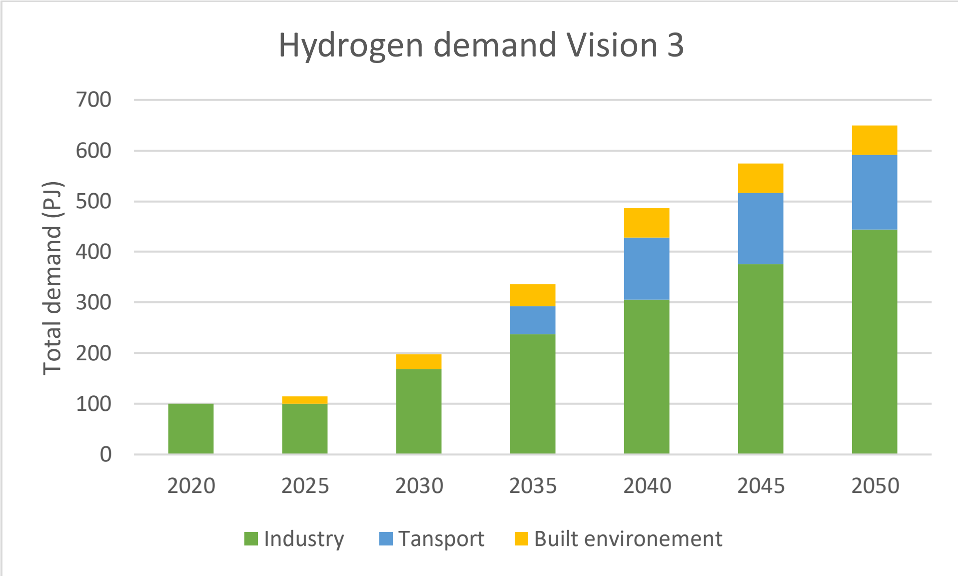

Figure 31 - Hydrogen demand per sectors between 2020 and 2050 for vision 3.

The infrastructure that is constructed will also enable increases in larger phases. In the maturation phase, hydrogen is implemented in every sector. Demand is still increasing, and cross boarder hydrogen infrastructure is built to import hydrogen. Green and blue hydrogen are used for inland production.

As seen in Table 34 key changes to the system are

- Providing supply of hydrogen for growing demand with green and blue hydrogen
- Construct hydrogen interconnection to import hydrogen on demand
- Create scale for hydrogen in industry, built environment and transport
- Provide an infrastructure that enables supply and demand growth of hydrogen
- Gain support for hydrogen on a large scale

The changes are driven by four key actors in the system, i.e. TSO, heat providers industry, DSOs, transport refuelling operators and hydrogen producers. The key actors have been identified during interviews where with several actors and potential actors the role of various stakeholders is discussed in more detail. Elements of the reports selected for vision comparison are also taken into consideration when selecting the key actors for vision 2. The key actors provide the backbone of hydrogen growth in order to realize vision 3. Table 34 summarizes how the key actors are influenced by vision 3.

		Development	Scale-up		Maturation	
		2019-2025	**2025-2030**	**2030-2035**	**2035-2040**	**2040-2050**
Cultural	*Behavioural*	Social acceptance hydrogen pipelines Gain trust and support of regulating actors in built environment	Corporate support Stay critical on hydrogen Focus on circular bio-based in industry			
	Educational	Research program on hydrogen Demonstration in built environment Educate on construction and operation hydrogen	Demonstration hydrogen vehicles	Demonstration heavy vehicles & inland navigation		
Structural	*Institutional*	Facilitate 3% adjustment in built per year Governmental leadership Set KPIs Collaborations with MVC Set company agendas 20-30 years	Stimulate company investment new tech Divide risk commitments Tenders blue hydrogen	Determine on quality hydrogen infra	Tenders electrolysis	
	Legal	Conditions hydrogen in built environment on safety Include hydrogen in Gas law	Set contracts for hydrogen projects Determine if infra becomes public	Regulations on grey hydrogen		
	Economic	Subsidy on CCS in SMR	Subsidy on blue hydrogen Long term investment plan infra	Socialize costs infra Subsidy on circular bio-based industry	Increase carbon tax Fiscal incentives hydrogen in transport Subsidies hydrogen in transport	Subsidies electrolysis
Technical	*Infrastructure*	Construct infrastructure built environment Natural gas infra to hydrogen	Design infra for future Make clusters with hydrogen infra Match supply & demand	Connect clusters Infra for various hydrogen quality Construct refuelling infra	Construct hydrogen infrastructure between countries	
	Production	Carbon capture infra From grey to blue hydrogen	Construct blue hydrogen capacity	Find efficient materials for electrolysis Construct small scale electrolysis	Industrialize production of electrolysis Design flexible system electrolysis	Scale electrolysis
	Market	Construct boilers in built Enable short term storage hydrogen	Scale hydrogen in built	Construct high temperature heat industry Implement hydrogen vehicles passenger and heavy	Implement hydrogen for inland navigation	Construct flexibility with hydrogen and electricity Use hydrogen with carbon to create new products
	R&D	Monitor technologies Research built environment Research on natural gas grid to hydrogen Research blue hydrogen	Research expansion of hydrogen infrastructure Research scaling transport	Research electrolysis Research storage hydrogen in salt caverns Research integration of sectors hydrogen		

Table 33 - Roadmap vision 3

Table 34 - Influence of vision 3 on key actors

Actor	**How is the actor affected by vision 3?**	**What action should the actor take to change the current system accordingly?**	**What may be the motivation behind the change?**
Gasunie & Tennet	Large total installed capacity electricity; need for large hydrogen grid; multiple energy carriers in system	Increase gird electricity; transform natural gas grid to hydrogen; maintain natural gas grid for blue hydrogen production; built hydrogen interconnection for import.	Enable grid of the future; new business opportunities
Heat providers industry	Different energy carrier for heating; consistent supply hydrogen	Adjust heating system for hydrogen; construct a reliable supply of hydrogen; construct back-up hydrogen	New business opportunities; emission reductions; demand change; regulations on emissions
DSOs	Large role out hydrogen in built environment; alternative natural gas grid; need for large hydrogen grid in built;	Adjust natural gas grid to hydrogen; construct hydrogen infrastructure to various regions; create scale hydrogen built environment; socialize costs	Alternative to natural gas for built environment heating; lowest social costs
Transport refuelling operators	Large demand for hydrogen; sufficient infrastructure for all transport demand;	Create large supply chain for hydrogen in transport; provide storage where necessary	New business opportunities; growing markets; reliability
Hydrogen producers	Large demand for hydrogen; need for consistent flow to cover demand; seasonal fluctuations with season in built environment	Provide sufficient supply of hydrogen; facilitate seasonal fluctuation storage hydrogen demand;	New business opportunities; reliability

In vision 3 when considering the pathways, scale is key. In the early stage of development and scale-up, the key actors will need support of the government. As soon scale is reached, costs of the hydrogen system will go down and hydrogen becomes the new regime in the energy system along hydrogen. Without strong governmental support, vision 3 cannot be realized. Even if companies would push for a hydrogen future, without governmental support, a large hydrogen future will not be realized in 2050 and vision 2 is more likely.

In the early stages support is necessary. Actions the government can take relate to bottlenecks to the system. The bottlenecks have been identified during the interviews as form of barriers as discussed in section 6.6 and the solutions have been elaborated on in the backcasting questions. While actors will have certain drivers for change, policy measures are still necessary to realize the vision. The most important bottlenecks for vision 3 are the cost of electrolysis, competitiveness of green hydrogen, competitiveness of blue hydrogen, competitiveness of hydrogen vehicles, competitiveness of high temperature heating, costs in built environment and the infrastructure of hydrogen. Table 35 shows the bottlenecks and policies for vision 3.

Table 35 - Vision 3 bottlenecks and policies

Bottleneck	**What needs to be done**	**Policy**
Costs electrolysis	Production cost reduction Reduction CAPEX	Subsidies for production improvements; tenders
Competitiveness green hydrogen	Reduce cost electricity Increase costs natural gas Improve efficiency	Provide feed-in tariff hydrogen; provide carbon tax; subsidies for improvements
Competitiveness blue hydrogen	Increase cost emissions	Regulations on grey hydrogen; provide carbon tax; provide feed-in tariff
Competitiveness hydrogen vehicles	Increase costs fossil fuels	Provide carbon tax; increase regulations on fossil fuel vehicles; subsidies/tenders for refuelling infrastructure
Competitiveness high temperature heating	Increase cost fossil fuels Create scale for heating in industry	Carbon tax; regulations; subsidies/tenders for high temperature heating; guarantee infrastructure
Costs built environment	Production costs boilers Scale boilers Increase costs fossil fuels Reduce costs hydrogen grid connections	Subsidies improvement production; tenders for boilers; socialize costs; provide carbon tax on natural gas in built environment
Infrastructure hydrogen	Determine regulatory framework infrastructure Provide funds infrastructure Built infrastructure for large demand	Define regulatory framework; provide tenders for hydrogen; include hydrogen infrastructure guarantee in tenders; determine infrastructure 2050

7.4 Visions compared

This section compares the investment costs of the three visions. Hydrogen production capacity investment costs are calculated for each vision, including electrolysis and SMR with CCS. First a description is provided how the CAPEX and efficiency is determined, before showing the results. The results of investment costs are compared. At last, predictions for development of hydrogen costs are compared for different production methods.

The costs for electrolysis are calculated based on Agora Verkehrswende, Agora Energiewende, & Frontier Economics (2018). As an alternative cost scenario targets are set for 2030 to have brought the CAPEX of electrolysis down to 350 euro/kW with an efficiency of 80% (Rijksoverheid, 2019; Waterstof Coalitie, 2018). The alternative target is when 3-4 GW of electrolysis is installed. For each vision 350 euro/kW with 80% efficiency is used as soon the capacity exceeds 3 GWs. For vision 1 this target is reached in 2040, for vision 2 2035 and for vision 3 2030. The average of both cost scenarios is used to calculate the costs.

For SMR with CCS, the results of the IEA (2019) are used. The CAPEX is converted from dollars to euros.[6] The difference between SMR and SMR with CCS is used to calculate the costs of CCS per kW. As an alternative route, the costs for CCS are 31% of the CAPEX in 2017 and 23% in 2030 (CE Delft, 2018). The average of both cost scenarios is used to calculate the costs.

The results for the investment cost are shown in Figure 32. The costs for SMR with CCS are combined with electrolysis to provide an overview of the total expected costs.

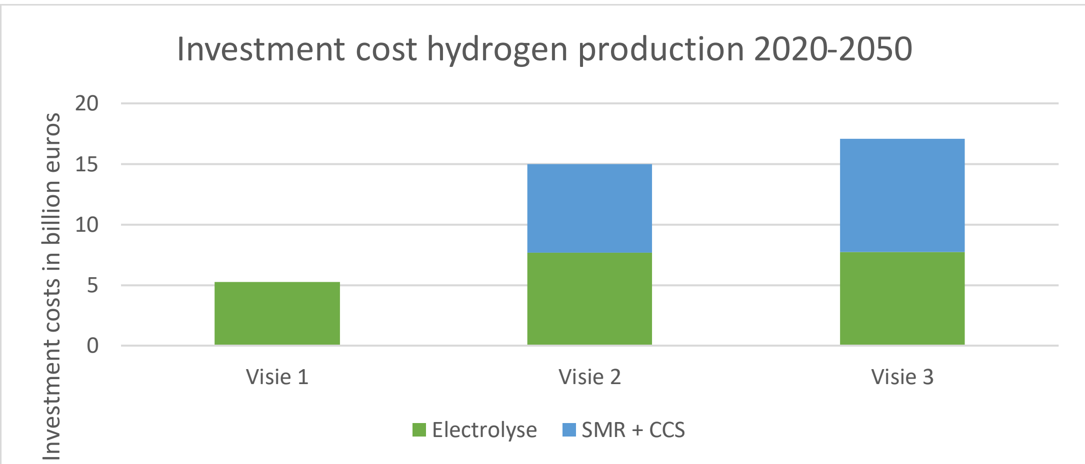

Figure 32 - Investment costs visions hydrogen capacity

[6] The currency for the 31st of December is used for the year 2017: 1EUR=1,2006USD.

Table 36 - Differences between scenarios in costs, CAPEX and efficiency

	Investment costs in billion euros	Varying CAPEX 2050 in euro/kW	Varying efficiency 2050 in %
Vision 1	3,6 – 6.9	275 - 600	74 - 81
Vision 2	5,6 – 9,8	238- 450	80 - 81
Vision 3	7,5 – 7,9	200	80 - 82

When the investment costs of the visions are compared some interesting things can be noticed. In vision 2 and 3, blue hydrogen is used. The costs are similar through the scenarios and therefore the difference between investment costs is caused by difference in additional installed capacity. In case of the investment costs for electrolysis, the investment costs do not differ much, while the installed capacity differs with 10 GW. The variety in results is due to a different technological development and cost reduction of CAPEX between the visions. Table 36 provides an overview of the range for investment costs, CAPEX and efficiency for each scenario. The range for CAPEX and efficiency is in case of vision 1 very small. The investment costs have therefore a small range between the scenarios. In case of vision 2, the range is much larger, due to variation in outcome. While in case of strong technological development, the costs for vision 2 will be almost 2 billion euros less than vision 3. Costs for vision 1 remain high per kW due to lack of technological development and scale.

How the costs for green and blue hydrogen production will develop is uncertain. Various studies have been conducted that make predictions. CE Delft (2018) provides in its predictions for the year 2040 results of electrolysis between 60-100 euros/MWh and for blue hydrogen between 45-75 euros/MWh. Navigant (2019) expects lower costs by 2050 for electrolysis dependent on source. In case of curtailed electricity, the price is between 17-71 euros/MWh strongly dependent on the full load hours (between 709-2881). North Sea wind provides a hydrogen price between 48-61 euros/MWh and imported hydrogen from Southern Europe varies between 44-59 euros/MWh. Blue hydrogen costs vary between 36 – 63 euros/MWh. The current hydrogen costs are roughly 30 euros/MWh. This means between grey, blue and green hydrogen needs to be covered in order to make investments in blue and green hydrogen feasible. Table 37 provides an overview of expected costs for hydrogen of electrolysis and the gap between grey, blue and green.

Table 37 - Overview of costs for hydrogen and the gap between grey, blue and green hydrogen.

Vision	Expected price green hydrogen in euro/MWh	Gap between grey and blue in euro/MWh	Gap between grey and green in euro/MWh
1	17 - 71	-	-47 - 41
2	48 – 61	6 - 33	18 - 31
3	44 – 61	6 - 33	14 - 31

For vision 1, the price for curtailed electricity has been chosen, because the electricity will mainly be provided by a surplus of offshore wind in vision. Vision 2 assumes green hydrogen is produced of offshore wind on the North Sea. Vision 3 combines offshore wind with import and therefore the price of North Sea wind and Southern Europe electricity are combined.

The gap between grey and blue and the gap between grey and green highlights the gap that needs to be overcome in order to make hydrogen competitive. On one side, carbon tax and stricter regulations can bring the price of grey hydrogen up, while subsidies on the blue and green hydrogen are necessary to bring the price down.

7.5 Conclusion Pathways and Roadmaps

This chapter has shown different results for pathways and roadmaps of hydrogen in the Netherlands. Vision 1 places emphasis on an energy system where hydrogen is used as a secondary energy carrier, electrolysis is scaled along offshore wind capacity. Key actors to facilitate the scale are involved in the current energy system and the current hydrogen system. Investment costs are lower than in the other scenarios, due to the small implementation of hydrogen. The costs on the other side of hydrogen are lower due to production of curtailed electricity.

Vision 2 places emphasis on hydrogen as secondary and primary energy carrier. A green future with electrolysis is aimed for, though blue hydrogen is seen as a transition production method to scale hydrogen for industry, built environment and transport. The investment costs for hydrogen are large, due to moderate technological development. The costs of electrolysis are challenging to overcome, due to the price difference between natural gas and offshore wind electricity.

Vision 3 places emphasis on hydrogen as primary energy carrier. Both blue and green hydrogen are used to enable the growth for hydrogen demand. The government and grid operators have a active role in facilitating an infrastructure that can match the growing demand and supply. Many stakeholders are involved in the process. The investment costs of vision 3 are high in terms of money, but due to technological development are not exceeding vision 2. The challenge for vision 3 is providing support to overcome the gap between grey and cleaner hydrogen production methods, i.e. blue and green.

8 Discussion

Assumptions and research decisions have been made during the study to gain results. The results and assumptions are discussed and compared with other studies. The discussion can be separated in 8.1 Limitations, 8.4 Feasibility visions, 8.3 Methodology and 8.5 Scientific contribution.

8.1 Limitations

This thesis constructed three visions for hydrogen in the Netherlands by 2050 and roadmaps with detailed information on how to reach the constructed visions. Limitations are present in the study due to assumptions and research decisions. The limitations that occurred are (1) boundaries to the scope of this thesis, (2) lack of workshops in participatory backcasting and (3) lack of modelling approach.

First, boundaries to the thesis scope have been selected. The boundaries form limitations to the thesis results which should be taken into consideration when reading the thesis. This thesis focussed solely on the development of hydrogen excluding the development of electricity, other energy carriers and hydrogen blending in the natural gas grid. While assumptions are made for the electricity system, the development and implementation of elements related to the electricity system are not taken into consideration. Involvement of other energy carriers, such as biomass and power-to-X, are left out of the scope. A research decision is made to focus on hydrogen and prefer hydrogen over biomass and power-to-X. In other studies those energy carriers are taken into consideration (European Commission, 2018; Gasunie & Tennet, 2019). In those studies, biomass and power-to-X will play a role in the system of 2050. At last, hydrogen blending with the natural gas grid is not taken into consideration. While in some studies, hydrogen blending is seen as a solution to decarbonize the natural gas grid, for this study it is assumed the natural gas grid will be dismantled by 2050 or reconstructed for other purpose (Hisschemöller et al., 2007). The boundaries form a limitation for this research, because all the elements do influence the potential of hydrogen.

Second, normally a participatory backcasting approach uses workshops to include stakeholders in the backcasting process. Workshops are used to construct visions and conduct the backcasting analysis. In this thesis a new approach for vision construction has been designed, because many visons on hydrogen were available. Due to limited time conditions, this thesis could not use workshops but uses an interview approach for the backcasting analysis. The different opinions of interviewees have been included in the construction of pathways and roadmaps; however different stakeholders did not collaborate to form a roadmap. A workshops approach may have led to more broadly supported pathways and roadmaps and more in-depth analysis of the potential of hydrogen in the different visions.

Third, a model has not been used to quantify the visions. The quantification of visions is based on assumptions. No energy modelling is used to provide quantitative measures. For each sector the situation has been determined for 2050, from there the potential of hydrogen was determined. Accordingly, calculations have been conducted to determine the demand for production measures (i.e. electrolysis, SMR and CCS). In interviews it was mentioned hydrogen projects are integrated through sectors and therefore strong interconnections occurs. Furthermore, the need of power balancing strongly depends on hydrogen demand, electricity demand and electricity generation with RES. Including those relations are very difficult without a model. Thus, modelling could contribute to explaining interactions of sectors, hydrogen and electricity in the visions. However, energy models also make assumptions of the interrelations of the different energy carriers. Furthermore, the more complicated a model the more difficult the predictions for the long term. Therefore, for simplicity this thesis the choice for not including a model has been made.

8.2 Broaden the perspective

As mentioned in section 8.1 both the scope and the lack of modelling may result in limitations of this study. Both widening the scope to multiple energy carriers and incorporating complex models for the relations between energy carriers could broaden the perspective of this research. However, adding these aspects may complicate the research, giving a larger variability of possible outcomes and thus more difficulty in substantiating roadmaps. It may prove useful to first conduct the methods of this study for different energy carriers to explore the future of the respective energy carriers. Afterwards complex models can be used to connect the respective futures of the carriers to provide more comprehensive prospects for the future.

8.3 Methodology

This section discusses the methodology and possible improvements. The methodological execution is compared to other studies and results for possible improvements. The comparison is done as follows: every step of the methodology will be reviewed to expose limitations, then the execution will be compared to other results.

8.3.1 Stage 1: system orientation

In the system orientation the problem is explored from a systematic view. Normative assumptions, requirements and targets are defined. Four different analysis are used to orientate the existing system, namely (1) system analysis, (2) stakeholder analysis, (3) vision comparison and (4) factor analysis.

In the system orientation the actor analysis can be more detailed by interviewing each stakeholder to determine their position. The actor analysis is now based on reports and interviews.

The vision comparison is a method that is different from other backcasting studies. The methodology of PESTLE has proven relevant to set the scope for vision construction. Involvement of workshops/interviews to provide the same set of information does not seem necessary because of the wide set of information found in the compared vision. The visions that have been analysed, often used workshops or interviews for the construction of visions or where conducted by stakeholders (e.g. Gasunie & Tennet, 2019; Gigler & Weeda, 2018; Hisschemöller et al., 2007). It can be questioned if workshops for this thesis would have led to different outcomes. After vision comparison, two new reports on hydrogen where found, i.e. Navigant (2019) and KIVI (2017). The visions will be compared to the constructed visions in the following section.

In further research a workshop approach can be compared with a vision comparison in existing literature to determine the differences between the two methods and if vision comparison leads to different outcomes than workshops with various stakeholders.

In this thesis it was necessary to translate the FCH and EC reports to the Dutch energy sector in order to compare the reports with Dutch reports. For the FCH only a share of the Netherlands in Europe was used. For the EC report, each sector was calculated separately. Due to another energy mix of the Netherlands than the rest of Europe, more accurate calculations can be provided to determine more specific elements in the European studies by looking into the details. For example, the distribution of different industries could be compared for Europe and the Netherlands to determine the hydrogen demand for 2050 more specifically.

8.3.2 Stage 2: vision construction

In vision construction, first, a vision is selected by choosing the key components for the vision with a morphological chart. After vision selection the vision is further constructed.

Vision 1, 2 and 3 are based on studies from the vision comparison of existing literature. Therefore, the results are limited to what has been researched an there is less space for including out of the box elements. The results are strongly influenced by the extremes in the analysed studies. The visions presented is a small representation of possible outcomes of the morphological analysis. When asked for feedback of interviewees on the visions, they understood the design choices made, since the visions are based on the common dilemma between electrons and molecules. Often interviewees related most to vision 2 which describes an integrated approach.

Two studies that were not included in the vision comparison, Navigant (2019) and KIVI (2017), are now compared to the constructed visions in this thesis. The Navigant study has a total energy demand for hydrogen of 6156 PJ for the EU by 2050. In their report, most demand is reserved for power balancing and industry (roughly 45% and 39%). Only a small share is assigned to transport and built environment (15% and 3%). If the demand for the sectors is translated to the Netherlands, the power sector entails around 135 PJ. This number is much larger than vision 1 where the focus of the vision is on hydrogen for power balancing. Transport (43 PJ) and built environment (8 PJ) show similar results to vision 2. The KIVI report only has a hydrogen demand for industry (187 PJ) and mobility (148 PJ) by 2050. Mobility overlaps with the demand in vision 3, while the demand in industry comes closer to vision 2. The visions described in these two reports could have influenced the vison construction; especially the study of Navigant could have influenced the outcomes in vision 1 on power balancing with hydrogen.

Finally, as mentioned in limitations, in this study no energy model is used. Calculations on the visions for quantification has been based on several literature sources. Other studies for the sectors in 2050 could have led to different results. Inclusion of an energy model could have led to a full energy system description with hydrogen.

8.3.3 Stage 3: Backcasting

In the backcasting stage a backcasting analysis has been conducted with interviews.

For the backcasting study, interviews have been used to gather information. In some backcasting studies, workshops are used to do the backcasting analysis. Due to lack of time, interviews are used instead. As a result, in some occasions results vary and stakeholders have different perspective on backcasting elements. Whether workshops lead to a better result is unknown. Further research could contribute to research the difference in approaches. On the other side it could be questioned whether during a workshop stakeholder influence each other's behaviour. Interaction may lead to other outcomes.

In some interviews design thinking elements were included, i.e. the method of change journey. It proved that design thinking methods in interviews are not useful, since the normal question already provided enough information and using the design thinking method requires a lot of time. During a workshop session the method could be more useful, because there is more time and its structures the way the group has to think and what elements they have to focus on.

When comparing the results of drivers and barriers to the studies of vision comparison no differences are found. Every driver or barrier mentioned in an interview can be found in the studies. Therefor2e, it can be concluded interviews may not contribute to new knowledge in comparison to country specific studies on hydrogen. It should be mentioned that some interviewees were involved in writing some of the analysed studies, what means there is a probability they gave the same answers to the questions than in other studies.

8.3.4 Stage 4 & 5: Pathway development & roadmapping

Interviews have only been conducted before the pathways and roadmap development. Specific questions for pathway development and roadmapping were asked to the interviewees, but often at the end of the interview. To improve the quality of pathway development and roadmapping, specifically assigned interviews and workshops with various stakeholders could be used.

In case of this thesis, with lack of workshops, validation of the roadmaps could contribute to improvements to the roadmaps. The roadmaps have been designed on elements mentioned in the interviews, however a more in depth-analysis could have been reached with validation of the outcomes. McDowall (2012) argues that roadmapping for transition should place more emphasis on ensuring good quality, transparent analytic and participatory procedures.

McDowall (2012) further elaborates on the fact that often roadmaps are designed in a one-off exercise. Inclusion of validation and/or workshops could benefit the quality of the roadmap. Stakeholders could provide more information on what specific governmental support is necessary for realizing the visions related to specific roadmap elements. Missing elements in the roadmaps could have been included. Though in the interviews the questions were asked on necessary policy measures, validation could provide new insights to a more detailed problem. Inclusion of stakeholders in the process is a way to secure participation. In terms of an academic study, embedding participatory commitment is not possible. Only workshops and interviews can provide insights in the position of stakeholders and how they would respond to certain visions.

The costs analysis is only conducted for hydrogen production. Other costs, such as infrastructure and hydrogen applications are not considered. They could be included in the study to compare the scenarios in more detail. Furthermore, costs of other energy carriers could be included to determine the full system costs.

8.4 Feasibility visions

This thesis constructed three visions for hydrogen in the Netherlands. The feasibility of the visions depends on certain indicators. The elements that influence the feasibility is the technological development of the technologies, the development of a global market and the costs for hydrogen. For each vision the three elements are discussed with a conclusion regarding the most feasible vision.

Vision 1 has the smallest investment costs in hydrogen; however, more investments will be necessary to enable an electricity system. Political support for electrolysis is feasible, because the risk of investments is at the utilities. They will see an opportunity for including electrolysis in offshore wind tenders. Though the government may support this inclusion by tenders, the subsidies for current tenders are already zero. Critique on vision 1 is on the large use of electricity. Especially grid operators will not favour this solution and also in sectors, high costs are related to some electricity alternatives.

Vision 2 has large investment cost for electrolysis and SMR with CCS. Since hydrogen is mainly used in industry with some extensions to other sectors, less investments are necessary in the infrastructure. The vision does not include an international market for hydrogen, though with the already existing hydrogen infrastructure through countries, it can be discussed if that element is feasible. An international hydrogen market may improve the development of hydrogen technologies. The selection of hydrogen application along electricity is widely supported by the interviewees. Furthermore, choosing hydrogen in case no other alternatives seem viable makes the vision more feasible. Challenges that may occur in the vision is the shift of blue hydrogen to green hydrogen.

For vision 3, 15 billion euros need to be invested in providing the necessary capacity up to 2050. Along the investments for capacity, subsidies, infrastructural investments, hydrogen application investments and many other costs are needed to realize the vision. It is the question whether the government and companies are willing to take the risk. Especially in case of vision

3, the government has to take many steps to reduce the investment risk for companies. In line with the current Climate Agreement in the Netherlands it does not seem viable the government is willing to decide on such a pro-active approach to enable large scale hydrogen integration. Furthermore, realization of a large infrastructure in an early phase is necessary. The implementation of a large infrastructure is not realistic. Also, for many sectors other alternatives such as biomass, steam and green gas may prove to be more applicable in industry, transport and built environment.

To conclude, vision 2 seems the most feasible vision. Vision 1 is not preferred based on the large share of electricity and the high costs related to that. Vision 3 is not preferred based on the high costs for hydrogen production, markets and infrastructure. Vision 3 is most likely to lack political support, due to the large upfront investment costs to enable the large scale-up. Though some elements for vision 2 should be adjusted it seems like the most feasible vision.

8.5 Scientific contribution

The scientific contribution describes the position of this thesis in literature and the scientific novelty that has been issued. First the thesis research approach is compared to other studies. Elements are compared and the conclusion leads to an adjusted research approach.

The approach of vision comparison to construct visions has never been done before. When considering the findings of an earlier backcasting study of (Hisschemöller & Bode, 2011). With Q-methodology the study distinguishes three possible visions, namely (1) hydrogen in the current infrastructure, (2) hydrogen in transport and (3) decentral renewable in built. The methodology of vision construction has led to very different visions in terms of implementation of hydrogen in various sectors. The use of vision comparison with a morphological chart has proven to allow for visions that include a wider range of elements.

Delpierre (2019) used a morphological chart instead of Q-methodology to construct visions. The analysis has led to a set of 8 dimensions, with varying dimensions compared to this thesis. Differences between the two theses can be found on the focus point of the studies. Delpiere constructs visons for electrolysis in the Netherlands to conduct a LCA. Two dimensions focus on the development of electrolysis. Furthermore, only transport is included as a potential market for hydrogen. The approach has led to three visions, i.e. pessimistic, optimistic and mixed. Similar range of visions can be found in this thesis, only varying between a focus on electricity, a focus on hydrogen or a combination of the two. The differences between the study of

Delpierre and this thesis are mainly caused by the scope of the visions and the reason why they are constructed.

The study of Ligtvoet et al. (2016) for construction of perspectives (similar to visions) Q-methodology was used too. From the Q methodology the participants were invited to workshop session. Workshops enable the inclusion of a diversity of views, dominant discourse and enabled learning among participating stakeholders. By using interviews to find results, there is no interaction between participating stakeholders what excludes the change to gain a mutual perspective. The study of Ligtevoet et al. further resulted in assumptions on stakeholders for the different perspectives. During the interviews for this thesis some of those elements for stakeholders where discussed, but discussion between stakeholders could have benefited for a more detailed description of the role of certain actors with their related actions and policy strategies to overcome barriers in the different roadmaps.

The backcasting study highlights drivers and barriers for hydrogen. Interviews are used to find drivers and barriers. The results are compared to scientific literature. Drivers found in literature for a transition to a hydrogen future are worldwide goals for climate change, energy security, local air quality and competitiveness (William McDowall & Eames, 2006). In this thesis though, climate change goals are not specifically mentioned as drivers, is it a main assumption for the vision development in first place to include Dutch climate goals. The dirver in literature, energy security, is matching the result found in this research for an increase of RES sources This leads to an increasing need for energy security. Local air quality and competitiveness have not been mentioned during interviews as drivers for hydrogen. For barriers studies are found that mention infrastructure for hydrogen as a barrier (Dunn, 2002; Konda et al., 2011; William McDowall & Eames, 2006; Shinnar, 2003). The focus is not on the costs of the infrastructure, but on the lack of existence. Furthermore, the implementation of hydrogen infrastructure is described as challenging. McDowall & Eames (2006) further elaborate on the costs and technological immaturity what is also find in this thesis. Especially the focus of the interviews was on the technological limitations and scaling in regard of maturity of technology. One barrier found in literature, namely the challenge of managing collaboration, is not mentioned as a barrier in interviews (Mcdowall, 2014), though the need for collaboration has been addressed.

Roadmapping is not broadly used in academic literature. McDowall (2012) describes a framework to understand how roadmapping relates to emerging theories of the governance system innovation. McDowall (2012) further elaborates the fact that credibility of a roadmap depends on the participation and commitment of key stakeholders whose actions are critical in further development of the system. Inclusion of stakeholders in the process is a way to secure participation. In terms of an academic study, embedding participatory commitment is not possible. Reports with roadmapping do occur and especially for the Netherlands. The following reports are considered for roadmap comparison, i.e. Gigler & Weeda, (2018), Noordelijke Innovation Board (2017) & Wijk et al. (2019). Gigler & Weeda (2018) provide a roadmap for hydrogen technologies. The roadmap provides a roadmap for technological development of hydrogen technologies. Development, market launch and mass production are indicators for the hydrogen roadmap. No other elements than hydrogen technologies are included in the study of Gigler & Weeda. The Noordelijke Innovation Board (2017) provides (1) a high level roadmap on hydrogen projects and how to scale hydrogen technologies and (2) a plan how the realization of green hydrogen economy in the Northern Netherlands should be organized. The realization of the hydrogen economy has been split up into five phases, (1) current phase, (2) masterplan phase, (3) backbone realization phase, (4) scale up phase, and (5) maturation phase up to 2050. Wijk et al. (2019) introduces an action plan for Zuid-Holland to enable hydrogen demand, supply, infrastructure and supporting policies. An in-depth roadmap for implementation of hydrogen is missing.

This thesis has used a combination of vision comparison for vision construction and roadmapping. The approach of vision comparison in combination with a morphological chart has shown promising results for further research. The inclusion of a roadmap is an active way to show the implementation of a vision. In order to expand the approach, emphasis needs to be placed on participation of stakeholders to better define their position within in the roadmap.

The comparison between existing literature and the work conducted in this thesis, an adjusted methodological framework is proposed:

Step 1: vision comparison and system analysis under the conditions

The method with vision comparison as a basis for vision construction seems promising for future research. With inclusion of a system analysis, no perspectives are left out. PESTLE-elements provide the basis for vision comparison.

Step 2: vision construction

The elements identified of the vision comparison form the basis for the morphological chart. From there visions are constructed.

Step 3: backcasting with interviews

The backcasting steps will be conducted through interviews with experts and stakeholders.

Step 4: modelling of energy system

A model will be made for the full energy system with hydrogen as defined in step 2. The model will enable to understand the relation between different energy carriers. Costs for the full system can be calculated.

Step 5: Workshop to design roadmaps, distinguish key actors and their role and policy strategy

The final step consists of participatory workshops with stakeholders. During the workshops, roadmaps are created, key actors are distinguished and their role. Incorporated in the roadmap a policy strategy is designed in order to enable realisation of the visions.

9 Conclusion

The main research question of the study is

How can hydrogen be integrated in the future energy system of the Netherlands by 2050 considering the various actors and steps that enable hydrogen?

By answering the sub questions the main research question can be answered.

What are developments, challenges and stakeholders of the current hydrogen system in the Netherlands?

The current hydrogen demand in the Netherlands is between 96 and 110 PJ/year. The hydrogen is produced for 80% by steam methane reforming and 20% as by-product. The hydrogen is used for 60% in ammonia production and 40% in (petro)chemical industry. Hydrogen is consumed in industrial clusters and therefore in the clusters a hydrogen infrastructure is present.

The Dutch government sees potential in hydrogen is energy carrier of the future to reach climate change goals. Potential markets for hydrogen are high temperature heat in industry, low temperature heating in built environment, heavy vehicles in transport, inland navigation, long distance passenger transport, storage and electricity production. Infrastructural adjustments are necessary to facilitate the increasing demand of hydrogen. The natural gas infrastructure can be used for hydrogen with adjustments or a new infrastructure needs to be constructed.

While production is currently done with steam methane reforming (referred to as grey hydrogen) other production processes are possible. Blue hydrogen includes carbon capture on steam methane reforming installation. Green hydrogen produces hydrogen from water and electricity in electrolysis. Especially electrolysis is considered a clean production process of hydrogen.

There are a few stakeholders involved in the current system. With ongoing developments, the number of stakeholders strongly increases. Several groups of actors can be identified, i.e. actors for the specific markets and actors that are involved in all potential markets.

How can similarities and differences of existing visions a provide potential visions for hydrogen in future energy systems in the Netherlands by 2050?

Various existing studies on visions for hydrogen have been analysed as input for vision selection. The visions are analysed on PESTLE-elements and their quantitative input. The summary of PESTLE-analysis is shown in Table 9. The comparison shows highest potential for hydrogen in industry compared to other sectors. Furthermore, whether hydrogen will play a role in built environment and to what extent in transport is questioned through the existing visions. The focus on industry is seen in later studies. Often hydrogen is compared to electricity as an energy carrier where emphasis is placed on a variety of visions. Hydrogen is often compared to other molecules such as biomass and methane. Import of hydrogen could play an important role in integration of various countries.

One of the differences, namely the discussion on electricity versus molecules, can be used as a basis for further vision development. As one extreme a full electric system is chosen, as another extreme a high level of hydrogen is chosen. In between the two extremes, a mixed vision is selected. With a morphological analysis based on PESTLE-elements a has been designed (Table 11). The morphological analysis forms the basis of vision construction.

What are visions and roadmaps for hydrogen futures in the Netherlands by 2050?

Three visions have been constructed based on the morphological chart (Table 11). Table 13 provides a quantitative summary of the visions. The three visions are as follows:

Vision 1: all electric describes a vision where electricity is chosen as the energy carrier of the future. Large offshore wind capacity is built, and the increase of RES demands flexibility and storage. Hydrogen is used for storage of electricity and hydrogen fired power plants are used for production of electricity. Furthermore, the current hydrogen production is fully reconstructed to green hydrogen production.

Vision 2: one integrated system combines best of two worlds, i.e. hydrogen and electricity. Hydrogen is implemented in built environment, industry for high temperature heating, heavy vehicle transport and inland navigation. The production of hydrogen comes from both green and blue hydrogen.

Vision 3: Go hydrogen describes a system where hydrogen is key and implemented in many sectors. Hydrogen is used in built environment, industry for high and medium high temperature heating, heavy vehicle transport, inland navigation and long-distance passenger transport.

A roadmap has been constructed for each vision

Table 27 shows the hydrogen roadmap for vision 1. Vision 1 describes a system where electricity is used as primary energy source. Hydrogen plays an important role in flexibility of the energy system. Electrolysis will be scaled fast to provide flexibility. Thus, support is needed for electrolysis in an early phase of the roadmap. The current production of grey hydrogen is after scaling of electrolysis replaced by green hydrogen. Scale is key to competitiveness of green hydrogen in the current hydrogen system.

Table 30 shows the hydrogen roadmap for vision 2. In case of vision 2 hydrogen production will change overtime. In the beginning blue hydrogen is supported to reduce emissions of the current hydrogen production. After further development of markets and hydrogen, green hydrogen is promoted to replace the blue hydrogen production. In built environment a similar transition is constructed. In early stages hydrogen is promoted with simultaneous promotion of energy efficiency measures in built environment. At the end of the vision, energy efficiency measures have improved, and alternative heating systems can be implemented.

Table 33 shows the hydrogen roadmap for vision 3. In vision 3 every action is to enable a large hydrogen economy in 2050. While development and scaling are to improve the technologies and supply chain. In the maturation phase hydrogen plays an important role as primary energy carrier in the energy system. Especially in the early stage, demonstration and governmental support are necessary to realize a hydrogen future.

What are implications of the roadmaps for actors, potential responses and policy strategies to overcome barriers in roadmaps to reach the desired outcome?

For each vison the key actors have been determined. The key actors for vision 1 are utilities, TSO, electrolysis manufacturers and current hydrogen producers. Table 28 shows how the key actors are influenced by vision 1. The key actors for vision 2 are TSO, DSO, current hydrogen producers and utilities. Table 31 shows how the key actors are influenced by vision 2. The key actors for vision 3 are TSO, heat providers industry, DSOs, transport refuelling operators and hydrogen producers. Table 34 shows how the key actors are influenced by vision 3.

Based on the roadmaps with key changes, bottlenecks have been identified. To overcome the bottlenecks of each vision policy measures can be used. Table 29 (vision 1), Table 32 (vision 2) and Table 35 (vision 3) summarize the bottlenecks for each vision with policy measures to overcome the bottlenecks.

To conclude, the main research question can be answered.

What are possible roadmaps to enable hydrogen futures in the Netherlands by 2050?

The main research question can be answered with the sub questions. Three possible visions have led to several levels of integration of hydrogen.

The first roadmap describes a vision with hydrogen as secondary energy carrier. Hydrogen is implemented with increasing capacity of offshore wind. Electrolysis capacity is included in offshore wind tenders and policy support focusses on enabling hydrogen in offshore wind tenders. Especially utilities, TSO, electrolysis manufacturers and current hydrogen producers are affected by the changes in the system.

The second roadmap describes a vision with hydrogen as primary and secondary energy carrier. Hydrogen is implemented in industry and as an extension integrated in other sectors. In order to facilitate the growth in demand for hydrogen, blue is in early stages promoted. In later stages, blue hydrogen is replaced by green hydrogen. Policy support is needed to enable competitiveness of blue and green hydrogen compared to grey hydrogen. Especially TSO, DSO, current hydrogen producers and utilities are affected by this vision.

The third roadmap describes a vision with hydrogen as secondary energy carrier. Hydrogen is implemented where possible. To create scale, blue hydrogen and green hydrogen are both used. The policy strategy is designed to facilitate a fast grow for hydrogen, with limiting barriers and construct a hydrogen infrastructure to facilitate increasing demand and supply. Especially TSO, heat providers industry, DSOs, transport refuelling operators and hydrogen producers are affected by the vision.

9.1 Recommendations for actors

From the study various recommendations can be provided for actors. The actors are Gasunie & Tennet, DSOs and the government.

Gasunie & Tennet play an important role in the energy transition. Hydrogen may provide a solution for the challenges with

- First, hydrogen offers a great opportunity for Gasunie to retain the current t natural gas infrastructure. Though considerations on quality of the infrastructure should be considered. For different applications, different qualities can be used. Gasunie should think for what applications and sectors, Gasunie can offer a solution. In the end multiple infrastructures could be in place partly operated by Gasunie.
- In the current energy system, electricity and gas is not connected. With the development of power-to-gas, the electricity system and gas system may become interconnected. Under the current regulations, Tennet is responsible for operation of electricity and Gasunie for natural gas. In case the natural gas infrastructure is redesigned for hydrogen, the two infrastructures can be interconnected with power-to-hydrogen. The question

remains who will become responsible for the interconnection. Currently Tennet solves imbalance by connecting utilities and other actors in the electricity grid. In future scenarios, this system could be performed in a similar way where third parties transform electricity in hydrogen. Another scenario could be where Gasunie, currently not responsible, will have electrolysis capacity and can perform power balancing of the electricity grid in collaboration with Tennet. The options need to be further explored by the two parties.

Recommendation for DSOs relate to a potential increasing demand of hydrogen in built environment and the use of the current natural gas grid.

- With the current developments of hydrogen in public debate may lead to social pressure towards hydrogen in the built environment. DSOs in collaboration with regions and municipalities should be realistic of hydrogen in the built environment. Under certain conditions, hydrogen may offer a solution in built environment and on short term energy efference measures are not going to be taken. DSOs should try to be objective when it comes down to hydrogen implementation in built environment.
- On the other side, DSOs should look carefully in to the natural gas grid and elaborate on plans how hydrogen could be used in the grid. Some projects are already actively researching and demonstrating hydrogen in built environment and natural gas infrastructure. When hydrogen is more widely integrated, opportunities in transport sector along built environment may arise.

Recommendations for the government relate to enabling hydrogen in future energy systems. While steps are taken to enable hydrogen, some additional actions can be taken.

- First, currently with the plans of the climate agreement, steps are taken to incorporation of hydrogen in the current energy system. It is aimed to reduce the price of electrolysis and electricity. The goals set by the government differ from studies conducted and may not be reached by 2030. In order to support green hydrogen, tenders and subsidies could be used instead. With offshore wind, prices reduced very quickly, and tenders can be written out without need for subsidy. Tenders and subsidies will reduce investment uncertainty, what came as a large barrier in current development of hydrogen projects. By setting certain targets of hydrogen implementation in sectors can reduce the investment uncertainty further.

- Second, keep monitoring technological developments. Hydrogen is for some application still in the development phase and not considered for application. The technology might be ready as an alternative in a couple of years and therefore, not all decision should be made within the next couple of years. Especially after 2030, hydrogen may become the leading technology for some applications. For applications where hydrogen is well developed, targets for integration should be set.
- Thrid, actively discuss the infrastructure with Gasunie and current hydrogen infrastructure operators. There are various ideas of how the infrastructure should be operated. Based on the development of the hydrogen market, different solutions should be implemented. By active communication with Gasunie and current hydrogen infrastructure operators, a consistent market design for a hydrogen infrastructure can be made.

9.2 Future research

In future research the approach of vision comparison could be further developed. The approach shows promising results, but the limitations should be further elaborated on. In other situation for future energy systems, vision comparison could offer a solution in case many studies have been conducted. To validate the limitations of the vision comparison, approach a study can be conducted on vision comparison versus workshops to construct visions.

In the study technical, economic and environmental modelling assessments have not been conducted. Modelling the visions can provide new insights in the pathways and roadmaps and may lead to differentiating quantification of the visions. Combining models with pathways studies can provide a better insight in the bottlenecks between technical possibilities and realisation of the vision.

At last, in scientific contribution a new methodological approach for backcasting studies with roadmapping is proposed. Studies could conduct research on this approach and elaborate on workshop integration for roadmapping.

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Appendix I – List of interviews

Name	Organization
Ad van Wijk	TU Delft
Chris Hellinga	TU Delft
Gert Jan Kramer	Universteit Utrecht
Albert van der Molen	Stedin
Noé van Hulst	Ministry of Economic Affairs
Steve Sol	Air Liquide
René Schutte	Gasunie
Jan Veijer	Gasunie
Matthijs Hisschemöller	Drift
Marcel Galjee	Nouryon

Appendix II – Interview questions

Short introduction of my research, study etc.

Ask permission to record interview and to use names. Quotes will be verified before used.

- Can you tell me more about your job and how this relates to hydrogen?
- How do you think the hydrogen system will look like in 2050?

I have constructed 3 visions

Vision 1: Electricity first

Hydrogen as secondary energy carrier. It is used for storage and industry. Production of hydrogen comes from surplus offshore wind. Large capacity of offshore wind is constructed to cover the peak demand on regular days. Main infrastructure will be private.

Vision 2: An integrated system

Hydrogen is used as both secondary as primary energy carrier. It is used for industry, built environment, transport and power balancing when the technology is proven better than others. Production combination of green hydrogen and blue hydrogen. Large storage facilities needed to cover seasonal fluctuations.

Vision 3: GO Hydrogen

Hydrogen used for industry, build environment, transport and power balancing to its full extend. Infrastructure public and central with international connections. Production based on green hydrogen. There is a real European hydrogen economy in place. Public infrastructure

1. Do you think these visions are realistic? Which one the most?
2. What are improvements to the visions? Should I change something?
3. What are the benefits of each visions?
4. What are challenges in order to realise these visions?
5. What role does (stakeholder company) fulfil in the different scenarios?
6. What actions/changes need to be taken in order to realize the visions?
7. Who should be involved in enabling those changes?
8. What sort of support is needed in order to take actions?
9. How do different actions relate to each other in time?
10. In the visions, which actors will fulfil the central role in the future system?

Appendix III - Calculations current system

High temperature heat in industry

High temperature in industry is calculated based on two studies of Blue Terra (2018) and CE (2015). The findings are shown in the table below:

Heat per temperature in industry

Source:	CE (2015)	CE (2015) & Blue Terra (2018)	Blue Terra (2018)	Blue Terra (2018)	CE (2015)	Blue Terra (2018)
Years	2013	2030	2050	2050	2030	2030
	PJ	PJ	PJ	Cm	Cm	Cm
<100	49	48	42	0,6		0,69
100-250	73	79	58	0,825	1,7	
250-500	123	95	86	1,225	2,04	
>500	259	236	200	2,85	5,08	
Total	504	459	386	5,5		

Transport

All the results for transport are based on data of CBS, PBL, RIVM, & WUR (2018). The changes in energy consumptions per mode in 2050 to 2005 are based on the European Commision (2018). The results are shown in the table below:

1,08 cm	is equal to	20%	2005*	Verandering					
				H2	COMBO	H2	COMBO	H2	COMBO
				0,2	1,08				
				cm	cm	%	%	PJ	PJ
Totaal			566	-2,02	-2,07	-37%	-38%	354,4940267	349,2500322
Wegverkeer			400	-2,68	-2,7	-50%	-50%	201,6403749	200,1577251
w.v.	Personenauto's		251					126,5451168	125,614638
	w.v.	Benzine	165					82,97207288	82,36198411
		Diesel	73					36,72397058	36,45394139
		LPG	14					6,84907331	6,798712477
	Lichte bedrijfsvoertuigen		60					29,98986074	29,76934706

	Zware bedrijfsvoertuigen		84					42,29220849	41,98123637
	Motor- en bromfietsen		5,6					2,813188856	2,792503644
			216						
Overig verkeer			122						
w.v.	Binnenscheepvaart 1)		27	-0,3	-0,28	-6%	-5%	25,15662305	25,25527647
	Zeescheepvaart 2)		81						
	Visserij 2)		3,7						
	Luchtvaart 3)		9,5	1,08	1,09	20%	20%	11,43962499	11,45727873
	Railverkeer 4)		1,4	1,1	1,3	20%	24%	1,727643546	1,780801809
Mobiele werktuigen			44						
w.o.	Landbouwwerktuigen		15						

Built environment

Built environment numbers are based on the report by CPB & PBL (2016). The values are shown below:

All values in PJ	2013	2030	2030	2050	2050	2030	2030	2050	2050
Heat demand		Low	high	Low	High	Decentral	Central	Decentral	Central
Households	345	320,85	295,18	256,81	215,72	189,83	151,87	115,42	69,25
o.w. Existing	345	320,85	269,51	229,09	153,49	122,79	88,41	52,16	22,95
Utility	170	159,8	134,23	118,12	81,51	68,46	54,77	37,79	22,68

Storage and power balancing

Electricity production in the Netherlands is shown in the table below (CBS StatLine, 2019).

	2018
	PJ
Net production electricity	396,4
Nuclear power	12,2
Coal	103,7

Oil products	4,6
Natural gas	203,2
Biomass	14,5
Renewable	49,8
Other	8,5

Development of offshore wind capacity is based on two sources, i.e. Rijksoverheid (n.d.) & RVO (n.d.). The values are shown in the table below with source.

Windpark operational	GW	Source
2019	1	RVO
2020	1,5	RVO
2021	0	
2022	0,7	Rijksoverheid
2023	1,4	Rijksoverheid
2024	0	
2025	1,4	Rijksoverheid
2026	0,7	Rijksoverheid
2027	0	
2028	2	Rijksoverheid
2029	0	
2030	2	Rijksoverheid

Appendix IV – PESTLEs vision comparison

	Platform Nieuw Gas
Political	- Aim to realize a clean, affordable and socially acceptable energy supply. - Less dependent on political instable and less well-disposed regions/countries. - Make clear decisions in early stage. In early stage chose for existing technologies to accelerate hydrogen. - Role hydrogen strongly influenced by developments abroad. - Actions for government: stimulate and structure Dutch activities, acknowledge subsidies for development and introduction of new technologies, and involvement in demonstration projects are determinative for penetration of hydrogen technologies in the Netherlands.
Economical	Bottleneck: no driver to introduce hydrogen - Hydrogen has potential to enable innovation and offer opportunities for Dutch supplying and manufacturing industry. Development of innovative hydrogen technology offers good economic opportunities for industry. - Good policy can lead to growth hydrogen industry in NL: role government to show opportunities. In public private financing first emphasis on public financing and a shift change over time. For learning curve investments in pilot projects without business case crucial! - Include hydrogen in policy instruments for sustainability - Exploit the non-economic drivers
Social	Bottleneck: social acceptance - Support of transition with demonstrations - Education - Collaborations between knowledge institutes, universities and companies enables growth of new technologies such as hydrogen. - Strong need for public-private partnerships to get the technology market ready and facilitate market conditions besides enabling opportunities for entrepreneurs. - Promote bundling initiative to increase efficiency policy instruments. Increase participation!
Technical	Bottleneck: fuel cell and hydrogen technology not commercially available - Government pushes for further development technologies - Demonstration needed for CCS in blue hydrogen production - Need for other energy carrier beside electricity. - Grey, blue and green.

	- 2050 40-75% on hydrogen in vehicles. Energy sources: coal with CCS, biomass, offshore wind. FCEV. - CHP (10-30%). Hydrogen in stationary and mobile applications: integration and synergy of energy systems. Stationary: early phase: micro CHP, source natural gas CCS, coal CCs and biomass, first: blend with Hydrogen,
Legal	Bottleneck: institutional acceptance, safety and regulation - Need for learning environment with flexible regulations and permit application. - Change in regulations often lead to large market innovations, increase technological innovations and lead to an increase in market efficiency. On transport option for zero emission vehicle regulation should be implemented in time. - Option: buyers pool: protected tenders in which the government becomes buyer with the purpose to further develop niche markets. Purposeful support by government will lead to increase hydrogen in industrial clusters and enable early development. Analysis of institutional aspects necessary that determine to successful implementation of transition pathways.
Environmental	- Hydrogen enabler of reductions in GHG emissions to reach climate goals under Kyoto. - Increase air quality due to mobility/ transport sector.

Hydrogen in the current infrastructure

Political	- Government should drive for research.
Economical	-
Social	- No need for new infrastructure what leads to less burden on society. - Residential areas can be left out of the scope. - Increase of decentral generation of electricity may lead to increase green hydrogen. - Households get CHP systems.
Technical	- Gas and electricity grids become integrated. - CHP on natural gas and CHP on hydrogen. - First 5% hydrogen in infra as a pilot. 2020: hythane. - Technical challenge to mix hydrogen in current infrastructure.
Legal	- New market structure from monopoly in natural gas to multiple suppliers. - Natural monopoly of natural gas infra allows for delivery of local to grid.

Environmental	- Reduction of natural gas in chain. - Question whether climate neutral.

Hydrogen in transport

Political	- Need for strong governmental policy to drive change and reduce emissions in transport sector. - Several options for policy instruments to make clean vehicles more interesting.
Economical	- Increase of demand for natural gas when used in transport sector. - Commercialize fuel cell vehicles questionable.
Social	-
Technical	- FCEV commercialized. - Green hydrogen option for the future in both transport and storage.
Legal	- Taxes on fossil fuels and less sufficient vehicles. - Measures to enable clean transport
Environmental	- Biofuels might have less emissions in case grey hydrogen. - Reduction of CO_2 with biomass and hydrogen.

Decentral Renewable in built

Political	- Feed-in regulations and tariffs are unfavourable. - Room for pilots in policy. Subsidies for pilots etc. needed. - Allow for local energy systems.
Economical	- Economic expensive to store electricity in hydrogen. - Uncertainty on investment of different technologies.
Social	- Citizens become self sufficient - Active role for municipalities, provinces, project developers, constructors and housing cooperatives
Technical	- Hydrogen storage of green hydrogen production. - Multiple technologies integrated: system vulnerability. - Storage of electricity is the challenge to overcome. In seasonal fluctuations.

Legal	- Flexible standards in legislation and regulations - Reduction regulations that limit local renewable energy systems.
Environmental	- Strong uncertainty on grid due to extreme weather conditions. - Enabling zero emission buildings

PBL

Political	- Less international dependency with hydrogen under increased RES - Chose various solutions to reach climate change targets
Economical	- Cost reduction needed fuel cells - Economic feasibility unlikely before 2050
Social	-
Technical	- Further development of technology hydrogen in different markets and electrolysis - Development processes and innovative technologies take long time to implement in system - Hydrogen as energy carrier - Application of hydrogen in heat with CHP systems.
Legal	-
Environmental	- Hydrogen a necessity to reach climate change goals

Noordelijke Innovation Board

Political	- Regional, national and EU level need to implement integrated green hydrogen economy development into their policy. - Dutch government pushes for natural gas reductions. - Dutch government should overcome barriers with financial measures or other incentives. - need for stable policy
Economical	- RES becomes competitive with fossil fuels. - Northern Netherlands thrives on agriculture and natural gas. Reduction of natural gas: Need for new markets. - Development of energy production and transportation region.

	- Create hydrogen hub for transportation by ship, pipelines and trucks. - Green certificates to facilitate more financial needs for going green. - Financial business case for green hydrogen. - proof of costs technologies. - solid business case needed and investment commitments. - proof of callability technologies
Social	- Hydrogen innovation/ start-up centres. - hydrogen trade fair and exhibition. - Need education and training in the production and us of hydrogen. - Research institutes should extend their research on hydrogen production, infra, storage, use and new applications. - costs for businesses, facilitated by government when needed: low social costs. - stakeholder management and engagement of large importance. - mental shift to radical transformation. - social acceptance of initiative is essential. use existing companies for gas knowledge
Technical	- Infrastructure in place in Northern Netherlands for natural gas and electricity. With offshore connection, offshore wind etc. - proof of safety.
Legal	- Hydrogen trading platform with (entry and exit system): Predefined quality criteria with an entry and exit fee. Independent parties that organize the trading and standard contracts with standard products for trading. Trading companies that want to take part in an up and coming hydrogen trading platform. - regulatory framework (currently hydrogen only for large-scale industrial production) should cover standers, regulations, permitting procedures, safety, environmental regulations and spatial planning). - green hydrogen certificates. - strict regulations for hydrogen users on safety. - market creation for industrial hydrogen. - need for stable regulatory framework
Environmental	- alternative for natural gas improves climate change. - less earthquakes because alternative natural gas.

Elektronen

Political	-

Economical	Need high cost reductions wind and electrolysis. 2/3 of costs are for wind and electrolysis
Social	-
Technical	- System with power to hydrogen and hydrogen to gas hydrogen plant. - Green gas for industry.
Legal	-
Environmental	Green hydrogen over blue hydrogen in RES system leads to reductions of GHG Emissions

Moleculen

Political	-
Economical	Costs for production facilities with CCS are less expensive than green hydrogen production.
Social	-
Technical	Hydrogen production from green and blue hydrogen. Green hydrogen used in built environment.
Legal	-
Environmental	Blue hydrogen production allows for carbon capture and use of hydrogen replaces carbon emitting alternatives.

A Clean Planet for All

Political	- Need for clear industrial policy to improve technologies. - Questions how to secure scarcity of raw materials to decarbonize system. - By being key actor in development of hydrogen: opportunity Dutch industry: gain technological leadership. In order to do so: leadership needed by require supporting domestic influence in research, creating the necessary conditions for innovation to materialise and reinforcing cooperative programmes for the development of technology. Provide a competitive advantage, creating cost savings and spurring innovation - Proper financing and possible adaptation of tariff schemes. - integrated point of view: energy systems need to be integrated.

	- Support R&D&I in fields where technology is not proven yet. - fair taxation policy and fossil fuel phase out of fossil fuel subsidies transport. - See low carbon future in industry as opportunity not as drawback. - Industry: need for sufficient market design in order to allow for low-carbon solutions before policy and innovative solutions will make sense. otherwise no large-scale investments. - Industry: regional coordination needed for creating new business networks along the technological development (demand and infra). - Policy framework should: facilitate investment, support innovation and incentivise all the necessary changes, without jeopardising the global competitiveness of the European industries. - Member States to make key decisions with respect to security of supply, network infrastructure, energy efficiency and renewable energy policies as well as research and innovation. Moreover, they need to decide on their energy mix and enter regional cooperation
Economical	- Sector coupling (joined markets). - Uncertainty economics of hydrogen, because related to high investment costs and unpredictable levels of demand as well as regulatory uncertainty. - Competitiveness transport hydrogen in heavy vehicles - Low carbon future can strengthen industry with new opportunities. - Penetration low carbon technologies slowed down by international competition. - Investment risk. - In transition discontinuity can arise in economic environment.
Social	- Cooperative programmes for development of technology. - Include local levels by engaging citizens and local authorities, addressing in synergy other local environmental challenges, crucial in time to deploy the necessary infra. - Convince consumers to go over on hydrogen. - Pace of renovation in households to improve efficiency under question. - Creation of green jobs with transition to low carbon future
Technical	- Further evolvement of technologies: performance and costs to scale up their deployment. - Search for alternatives raw materials (scarcity) / challenge from electricity production following demand to meteorologically driven production (weather dependency). - Security of supply - Technological integration of various energy systems. - Technological feasibility for hydrogen in transport. - Hydrogen challenges for infrastructure compared to e-gas/fuels. - Avoid technology lock in in early stage.

	- Industry: need for sufficient infrastructure in order to allow for low-carbon solutions before policy and innovative solutions will make sense. - Penetration of technologies and building of infrastructure in time is critical. Further research needed difficult sectors to decarbonize (transport - aviation).
Legal	- Regulatory supporting scheme to enable financing and possible adaptation of tariff schemes. - Regulatory framework should facilitate the major change in energy market structure.
Environmental	- Raw material use (scarcity). - Hydrogen over e-gas/fuels: less land use and energy resources. - Different means to reach 85% targets with for some for sectors still use of fossil fuels

Routekaart Waterstof

Political	- Need for integral vision on hydrogen in energy agreement - Need for long term innovation program - No overall policy on hydrogen to develop the full spectrum of hydrogen
Economical	- Use of existing natural gas infra: cost effective energy transition - High cost price: need for reduction of costs electrolysis before competitive - Costs hydrogen strongly dependent on electricity price (renewable) - Financing of hydrogen future strong indicator succeeding of hydrogen - Market development (trading system). Natural gas trading platform could be an example. - Human capital to facilitate transition - Potential import of hydrogen - Scenario hydrogen industry mover form Netherlands to other countries - Scenario: need for hydrogen import
Social	- Hydrogen enables social challenge to become sustainable - Social acceptance strong indicator succeeding of hydrogen. Especially applications where consumer directly use hydrogen. - CCS application might be problematic in social debate. - Hydrogen projects with pilots - Human capital agenda: education
Technical	- satisfies demand for molecules, for example in transport - Electrolysis offers flexible mechanism for increasing RES - Proof of technologies on large scale

	- Enables long distance transport of energy - Increase needed efficiency technology - Develop new processes with hydrogen - Application of less rare materials - Hydrogen has many production and application possibilities. - From technical perspective, SRM not even the most viable option for hydrogen production. Biomass could offer a solution. - Need for infrastructure dependent on market development
Legal	- Laws and regulations to enable hydrogen - Stimulation structures for production and use of hydrogen. - Lack of regulation for introduction of hydrogen. Currently only on the industry application - Gaswet offers no flexibility hydrogen for transport and distribution of hydrogen. Inclusion of hydrogen in gaswet. - Discussion between private and well-regulated hydrogen grids - Subsidies for innovation projects Not for hydrogen inanities. No structural subsidy system for hydrogen. - European subsidy schemes - Safety program needed for hydrogen. Is under development, progressing slow due to financial support. - Trading system for hydrogen. Determine product specification within trading system.
Environmental	- Hydrogen enables reaching climate goals - On short term blue hydrogen production leads to emission reductions - Can potentially be fully climate neutral

FCH

Political	- Sector coupling. - Ramp up of hydrogen should start now! - Reaching goals: coordinated approach by policymakers, industry and investors
Economical	- Drive economy by becoming leading in hydrogen economy worldwide (820 billion annual revenue). - Create jobs with hydrogen
Social	- Customer preference and convenience: adaptation difficulties. - Hydrogen will offer same quality of life (transport range)/ invisible transition. Note: critique that there will be averseness to hydrogen.

	- Job creation.
Technical	- Technology is technical ready for implementation to reach goals for 2030 in transport, buildings, industry and power systems. - Hydrogen key to integration of mix ultra-low carbon sources. Key role electrolysis and SMR with CCS. - Electrolysis enables sector coupling and enables grid connection between the two carriers. - Hydrogen can replace natural gas in CHP system. - Hydrogen enables the decarbonisation of transport and industry sector. - Hydrogen allows for usage of surplus RES.
Legal	- Guarantees of origin should be used and embraced by regulation and national policy makers - Modernize and harmonize regulation that concern hydrogen blending into the natural gas grid. - Provide regulatory framework for hydrogen grid - Regulations should place incentives on transport sector to encourage certain investments
Environmental	- Only 560 Mt annual CO_2 abatement. 15% reduction of local emissions relative to road transport

To a green hydrogen action plan in the province of Zuid-Holland

Political	- In order to decarbonize industry, support blue hydrogen - Import hydrogen - Develop incentive policy for hydrogen refueling stations - Policy on spatial planning local green hydrogen - Plans for reconstructions from natural gas to hydrogen in Regionale Energie Strategie - Challenge to develop demand, supply and infrastructure simultaneously. - From a national approach that realizes the necessary preconditions to regional programs with specific designs for industrial clusters and spatial area. - Province Zuid Holland can act on its own without national support.
Economical	- Large industrial area in Zuid Holland. - Globally production of solar and wind will increase with decreasing costs. - Green hydrogen will become cost competitive with grey hydrogen. - Global market hydrogen with import

Social	- Education and training hydrogen for aid workers, police, fire brigade and safety regions etc. - Collaboration needed between government, market parties, knowledge institutes, grid operators and social organizations.
Technical	- Use existing natural gas pipelines for hydrogen - Hydrogen for peak demand in heat-hydrogen roundabout
Legal	- Facilitate and regulate public hydrogen transport infrastructure - Provide incentive schemes to enable hydrogen - Regulate spatial planning local green hydrogen - Development of permit structure, supervision and enforcement
Environmental	- Spatial use with local green hydrogen - Decarbonization of industrial area - Blue hydrogen as transition production process.

Local

Political	- Driver for transition: municipalities and city councils: emphasis on energy independency at a national level - No energy exchange with other countries
Economical	-
Social	-
Technical	- Power-to-gas (electrolysis with solar power). - Need for storage of hydrogen and methane of 16 TWh and 22 TWh
Legal	-
Environmental	- Own RES production of wind and solar: inefficient land use

National

Political	- Driver for transition: national governments: aim for a high degree of energy self-sufficiency on national level - Limited energy exchange with other countries

Economical	-
Social	-
Technical	- Power-to-gas (electrolysis with large scale wind power). - Strong need for considerable amount of flexibility from hydrogen-to-power and battery storage to cover fluctuations wind power. - Need for storage of hydrogen and methane of 20 TWh and 15 TWh
Legal	-
Environmental	-

International

Political	- Global oriented policy - Import of high RES potential countries - Depended for energy demand
Economical	- Large import of hydrogen, methane and/or e-fuels
Social	-
Technical	- Need for storage of hydrogen and methane of 12 TWh and 20 TWh
Legal	-
Environmental	-

Appendix V – scenarios A clean Planet for All

Long Term Strategy Options								
	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

Appendix VI – Potential table Gigler & Weeda

Table 38 - Indicative assessment of potential demand of hydrogen in the Netherlands

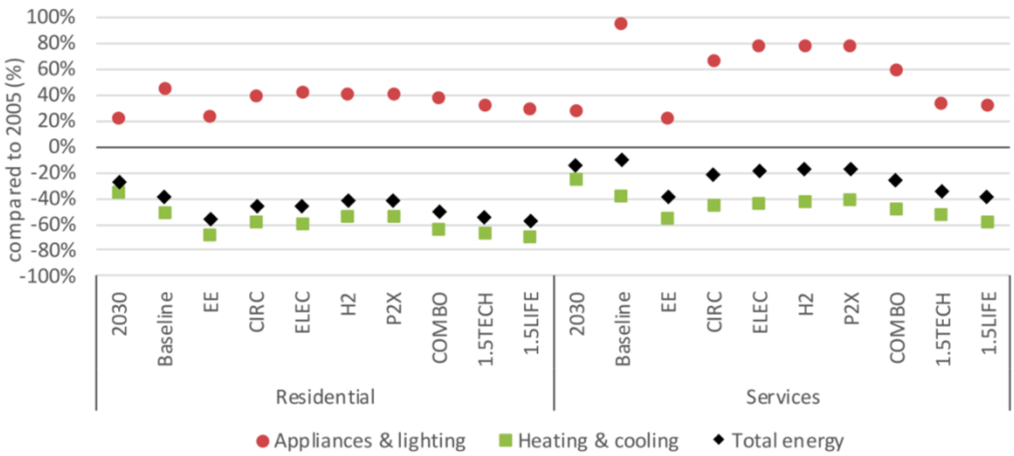
Functionality	Hydrogen demand		Offshore wind electrolysis		Natural gas/CCS reforming	
	PJ/j	Mton/j	TWh/j	GW	PJ/j	Mton CO_2 /j
Hightemperature heat:	1350	11,2	568	129,7	1800	111,8
Non-energetic use	*50*	*0,4*	*21*	*4,8*	*67*	*3,8*
Process heat	*100*	*0,8*	*42*	*9,6*	*133*	*7,5*
Reneable chemistry	*480*	*4*	*202*	*46,1*	*640*	*46,2*
Renewable fuels	*700*	*5,8*	*295*	*67,3*	*933*	*52,8*
Steal production	*20*	*0,2*	*8*	*1,9*	*27*	*1,5*
Mobility and transport	125	1	53	12	167	9,4
Power and light	115	1	48	11,1	153	8,7
Lowtemperture heat	100	0,8	42	9,6	133	7,5
	1690	**14,1**	**711**	**161**	**2253**	**128**

Appendix VII – Calculations European Commission

Built environment

Built environment final energy demand and share of hydrogen is calculated with figures of A clean planet for all (Figure 33, Figure 34 & Figure 35). The measurements and calculations to come to the end result are shown in the tables below.

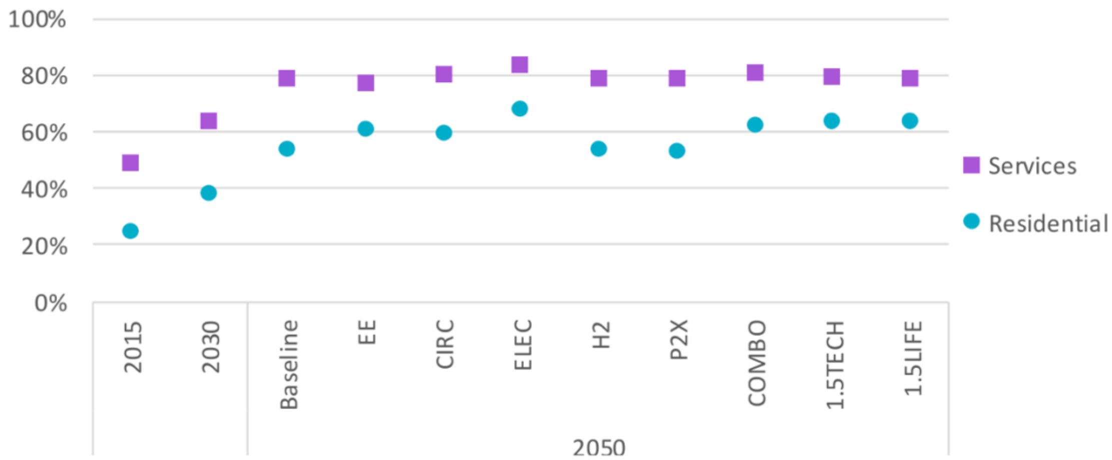
Figure 39: Evolution of the energy consumption in buildings in 2050 (compared to 2005)



Note: "Heating and cooling" includes space heating, water heating, cooking and air cooling.
Source: Eurostat (total sectoral energy consumption in 2005), PRIMES.

Figure 33 - Figure 39 A clean planet for all (European Commission, 2018, p.99). Ratio: 0,57 cm is 20%.

Figure 42: Share of electricity in final energy demand buildings



Source: Eurostat (2015), PRIMES.

Figure 34 - Figure of A clean planet for all (European Commission, 2018, p.103). Ratio 1,1 cm is 20%.

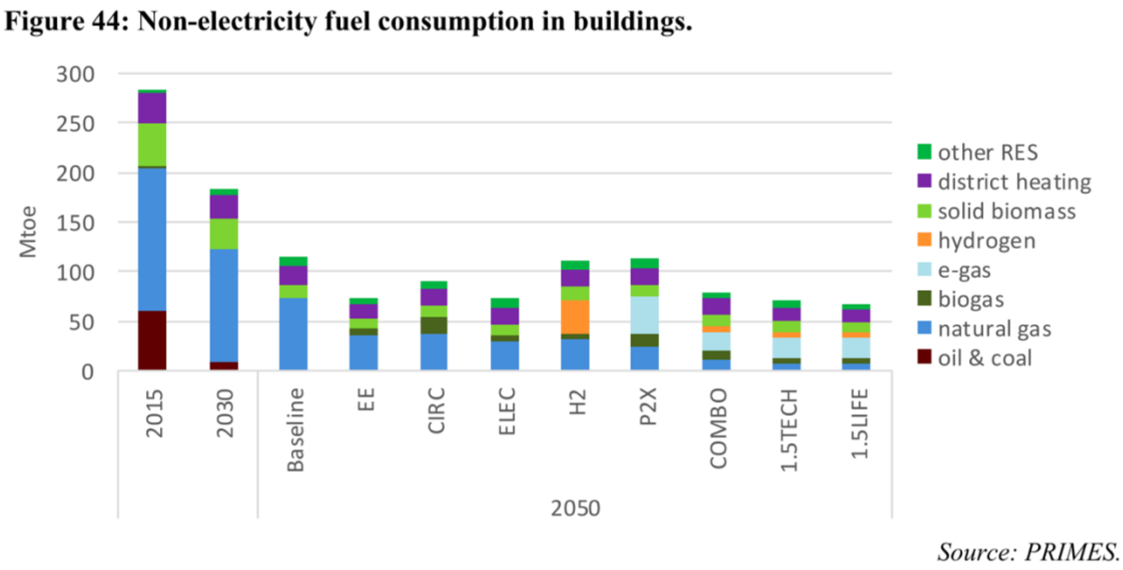


Figure 35 - Figure of A clean planet for all (European Commission, 2018, p.105). Ratio: 1 cm is 50 Mtoe.

The data of Europe is compared to the Netherlands. The table below shows the data as gained form EUROSTAT.

		EU 2015	EU 2005	NL 2005	NL/EU	NL 2015
Households	25%	11905,15	12982,97	450,0329	0,034663	401,6152
Services	14%	6374,411	6030,676	290,7106	0,048205	284,746
House+services	18279,56115	18279,56	19013,64	740,7435		686,3612
Share house	65%		68%	61%		
Share service	35%		32%	39%		

The information of the figures and data on countries forms the basis for calculations of the various scenarios in the Netherlands by 2050.

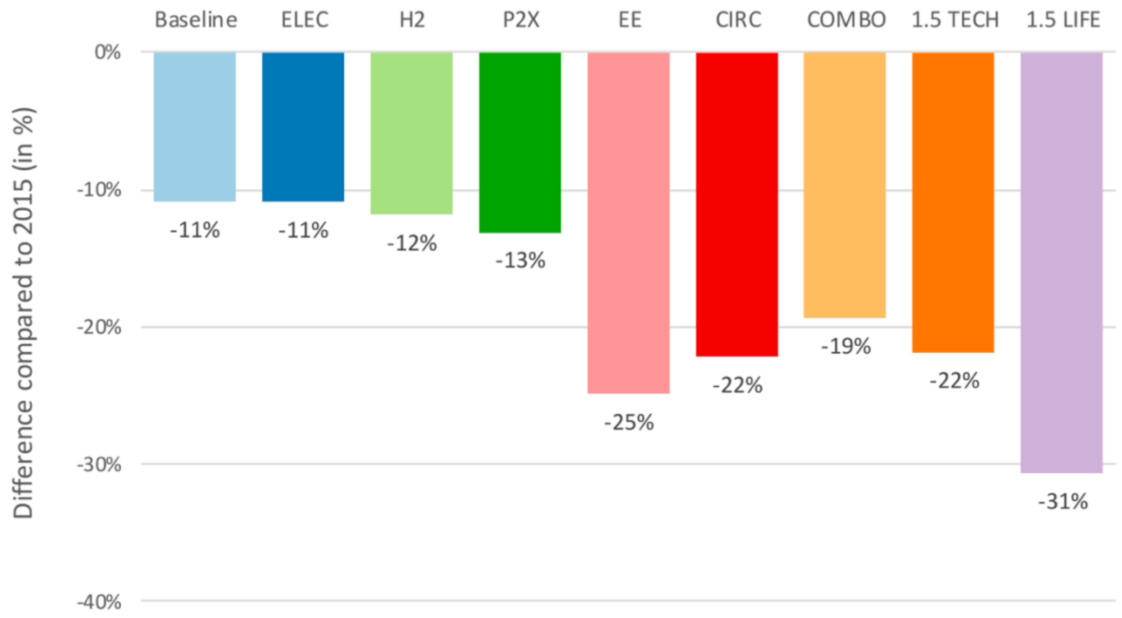
	Baseline	ELEC	H2	P2X	COMBO	1.5 TECH
Household elec (fig 42) cm	2,9	3,7	2,94	2,9	3,37	3,42
Service elec (fig 42) cm	4,25	4,54	4,25	4,25	4,35	4,29
Non electric households (fig 44) cm	2,27	1,45	2,2	2,25	1,56	1,44

Change energy consumption residential (fig 39) cm	1,07	1,27	1,15	1,15	1,4	1,5
Change energy consumption service (fig 39) cm	0,28	0,51	0,48	0,48	0,7	0,95
Household %	52,7%	67,3%	53,5%	52,7%	61,3%	62,2%
Service %	77,3%	82,5%	77,3%	77,3%	79,1%	78,0%
Change residential to 2005	38%	45%	40%	40%	49%	53%
Change services to 2005	10%	18%	17%	17%	25%	33%
Energy consumption in buildings in PJ EU	13546,84773	12149,08	12759,21	12759,21	11154,83	10170,28
Electricity in PJ EU	8477,711384	8929,244	8014,855	7958,533	7645,497	6960,025
Share residential final demand buildings EU	59,86%	59,24%	60,70%	60,70%	59,22%	60,47%
Non in PJ EU	5069,136341	3219,832	4744,354	4800,675	3509,329	3210,251
Share of electricity	62,6%	73,5%	62,8%	62,4%	68,5%	68,4%
Buildings hydrogen in PJ EU	0	0	1465,38	0	209,34	209,34
Share hydrogen buildings	0	0	11,48%	0,00%	1,88%	2,06%
Share of non elec	0	0	0,308868	0	0,059652	0,06521
Final non elec demand NL	192,4504005	123,3139	179,8898	181,8421	134,5269	123,2559
Final energy demand NL	**543,2227469**	**488,1806**	**510,1895**	**510,1895**	**448,2721**	**406,9806**
Hydrogen in buildings NL	**0**	**0**	**55,56225**	**0**	**8,024854**	**8,037497**

Industry

Industry final energy demand and share of hydrogen is calculated with figures of A clean planet for all (Figure 36 & Figure 37). The measurements and calculations to come to the end result are shown in the tables below.

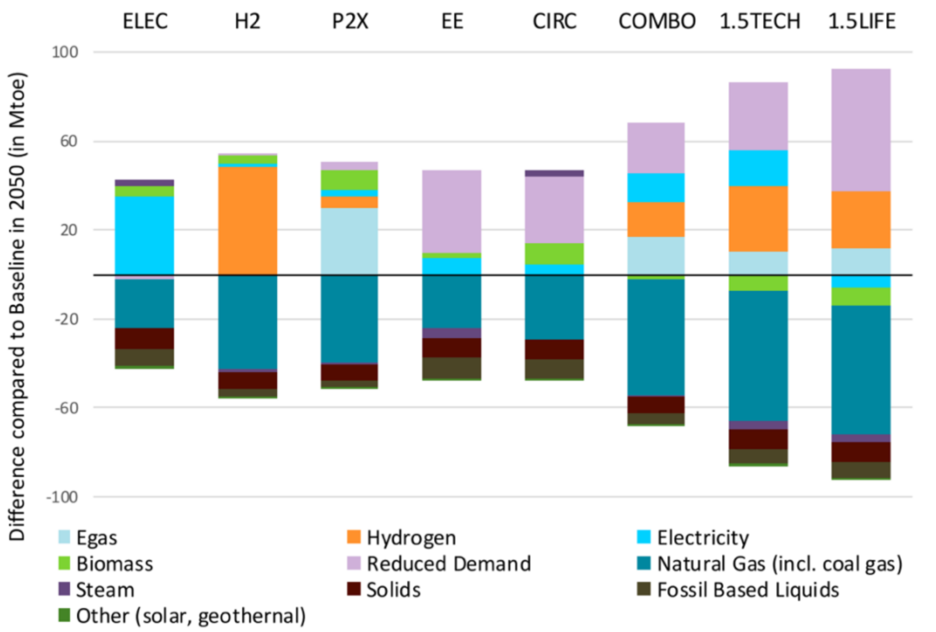
Figure 68: Total final energy consumption in industry by scenario compared to 2015



Source: PRIMES.

Figure 36 - Figure 68 A clean planet for all (European Commission, 2018, p.150).

Figure 69: Differences in final energy consumption in industry compared to Baseline in 2050



Source: PRIMES.

Figure 37 - Figure 69 A clean planet for all (European Commission, 2018, p.151). Ratio: 0,97 cm is 20 Mtoe.

The data of Europe is compared to the Netherlands. The table below shows the data as gained form EUROSTAT.

	2015 EU	2015 NL	NL/EU
Final energy consumption industry PJ	10656,22	562,2598	0,052764

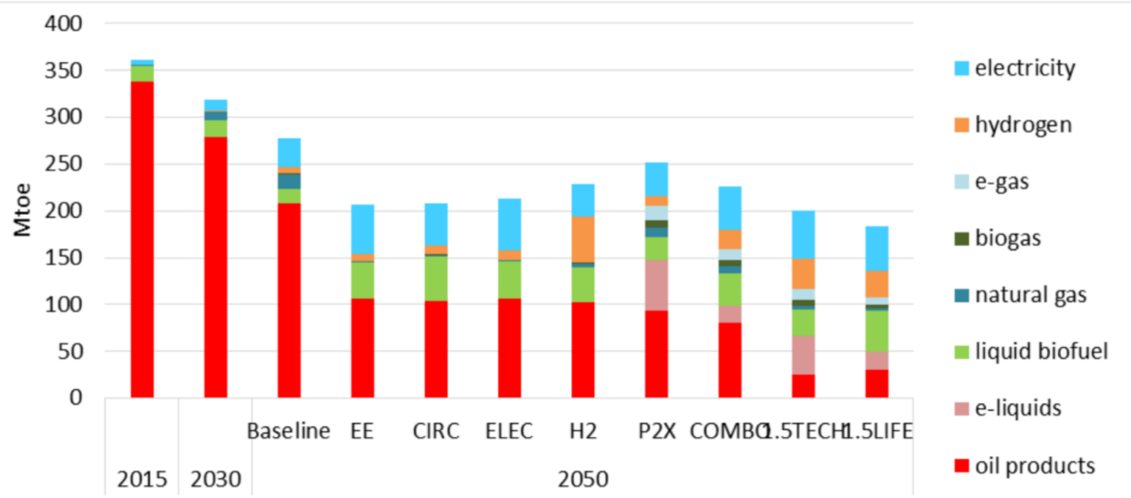
The information of the figures and data on countries forms the basis for calculations of the various scenarios in the Netherlands by 2050.

	ELEC	H2	P2X	COMBO	1.5 TECH
Difference final energy consumption industry to 2015	-11%	-12%	-13%	-19%	-22%
Hydrogen industry in cm	0	2,4	0,25	0,74	1,43
Final energy consumption 2050 NL	500,4113	494,7887	489,1661	455,4305	438,5627
Hydrogen industry EU in PJ	0	2071,819	215,8144	638,8107	1234,459
Hydrogen industry NL in PJ	**0**	**109,3165**	**11,38714**	**33,70592**	**65,13442**
% hydrogen in industry	0,0%	22,1%	2,3%	7,4%	14,9%

Transport

Transport final energy demand and share of hydrogen is calculated with a figure of A clean planet for all (Figure 38). The measurements and calculations to come to the end result are shown in the tables below.

Figure 57: Fuels consumed in the transport sector in 2050



Source: PRIMES.

Figure 38 - Figure 57 A clean planet for all (European Commission, 2018, p.131). Ratio: 0,92 cm is 50 Mtoe.

The data of Europe is compared to the Netherlands. The table below shows the data as gained form EUROSTAT.

	EU 2005	NL 2005	NL/EU
Final energy consumption in PJ	13619,29	476,396	0,03498

The information of the figures and data on countries forms the basis for calculations of the various scenarios in the Netherlands by 2050.

	ELEC	H2	P2X	COMBO	1.5 TECH
Hydrogen in sector 2050 in cm	0,2	0,9	0,19	0,4	0,6
Final consumption in transport in cm	3,9	4,2	4,6	4,14	3,68
Hydrogen in sector 2050 in PJ	455,087	2047,891	432,3326	910,1739	1365,261
Final consumption transport in PJ EU	8874,196	9556,826	10467	9420,3	8373,6
Hydrogen transport 2050 NL PJ	**15,91872**	**71,63422**	**15,12278**	**31,83743**	**47,75615**
Final consumption transport PJ NL 2050	310,415	334,293	366,1305	329,5174	292,9044
Percentage hydrogen of total NL	5,1%	21,4%	4,1%	9,7%	16,3%

Storage

Total energy storage is calculated with a figure of A clean planet for all (Figure 39). The measurements and calculations to come to the end result are shown in the tables below.

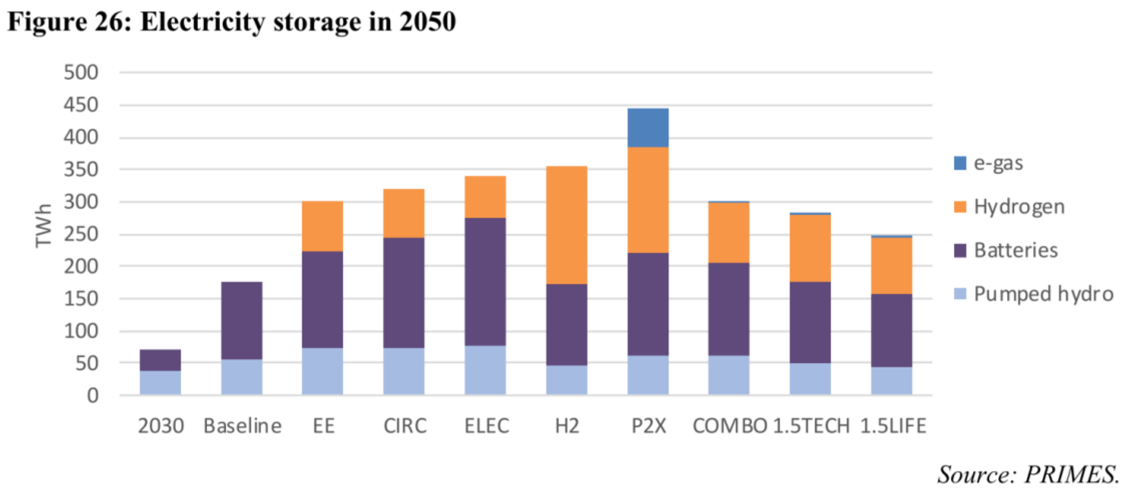


Figure 39 - Figure 26 A clean planet for all (European Commission, 2018, p.79). Ratio: 0,79 cm is 50 TWh.

The data of Europe is compared to the Netherlands. The table below shows the data as gained form EUROSTAT.

2015	In Mtoe

EU	1088,27
NL	49,19778

The information of the figures and data on countries forms the basis for calculations of the various scenarios in the Netherlands by 2050.

Share NL in total	0,0452073				
	ELEC	H2	P2X	COMBO	1.5 TECH
Hydrogen storage in cm	0,88	2,4	2,16	1,21	1,38
Total storage in cm	4,48	4,67	5,85	3,9	3,68
Hydrogen storage in TWh	55,696203	151,8987	136,7089	76,58228	87,34177
Total storage in TWh	283,5443	295,5696	370,2532	246,8354	232,9114
%	19,6%	51,4%	36,9%	31,0%	37,5%
Hydrogen in NL in PJ	**9,0643571**	**24,72097**	**22,24888**	**12,46349**	**14,21456**
Total storage in PJ	46,145818	48,1029	60,25737	40,17158	37,90549

Appendix VIII – Calculations FCH

	2015
EU (Mtoe)	1088,27
NL (Mtoe)	49,19778
NL/EU	0,04768

Year		Final energy demand	Thereof H2	Existing feedstock	New industry feedstock	Industry energy	Heating and power of buildings	Transportation	Power generation, buffering
2015		14.100	2%						
2030	BAU	11500	4%						
	Ambitious		6%	3,7%	0,5%	0,1%	0,3%	0,6%	0,6%
2050	BAU	9300	8%	4,2%	0,0%	0,6%	2,2%	0,9%	0,5%
	Ambitious		24%	4,2%	2,8%	2,5%	6,2%	7,3%	1,2%
2050	NL BAU in PJ	1649	8%	-	-				
	NL Amb in PJ		14%	-	-				

Appendix IX – Morphological charts visions

Vision 2

Production	Infrastructure	Markets	Political	Economic	Social	Technological	Legal	Environmental
Electrolysis	Decentral	Current market	Strong political support hydrogen	Electricity to natural gas ration high	Strong social support hydrogen	High development hydrogen technologies	Pro-active institutional change for hydrogen	Support green hydrogen to reach climate goals
SMR	Central	Industry high temperature heating	Moderate political support hydrogen	Electricity to natural gas ration moderate	Moderate social support hydrogen	Moderate development hydrogen technologies	Interactive institutional change for hydrogen	Support electricity to reach climate goals
SMR with CCS	International	Power balancing	Low political support hydrogen	Electricity to natural gas ration low	Low social support hydrogen	Low development hydrogen technologies	Passive institutional change for hydrogen	Support blue hydrogen to reach climate goals
Import		Built environment						Support biomass to reach climate goals
		Mobility heavy vehicles						
		Transport non-heavy vehicles						
		Alternative industrial processes						

Vision 3

Production	Infrastructure	Markets	Political	Economic	Social	Technological	Legal	Environmental
Electrolysis	Decentral	Current market	Strong political support hydrogen	Electricity to natural gas ration high	Strong social support hydrogen	High development hydrogen technologies	Pro-active institutional change for hydrogen	Support green hydrogen to reach climate goals
SMR	Central	Industry high temperature heating	Moderate political support hydrogen	Electricity to natural gas ration moderate	Moderate social support hydrogen	Moderate development hydrogen technologies	Interactive institutional change for hydrogen	Support electricity to reach climate goals
SMR with CCS	International	Power balancing	Low political support hydrogen	Electricity to natural gas ration low	Low social support hydrogen	Low development hydrogen technologies	Passive institutional change for hydrogen	Support blue hydrogen to reach climate goals
Import		Built environment						Support biomass to reach climate goals
		Mobility heavy vehicles						
		Transport non-heavy vehicles						
		Alternative industrial processes						

Appendix X – Calculations visions

Flexibility and storage: difficult to calculate without an energy model. The following assumptions are made:

- A clean planet for all has calculations for electricity storage demand in 2050. The demand has been calculated based on the share of the Netherlands in EU. Vision 1 uses ELEC scenario, Vision 2 uses COMBO and vision 3 uses H2. Based on the earlier numbers the total demand for storage has been calculated
- In a clean planet for all, pumped hydro, batteries and hydrogen is considered. Pumped hydro is not possible on Dutch grounds and therefore the solutions for electricity storage are not used as in a clean planet for all. Numbers for storage are based on Gasunie & Tennet. They focus on batteries and hydrogen.
- Vision 1 has a large capacity of offshore wind similar to the national scenario of Gasunie & Tennet. In that scenario the installed capacity for hydrogen and batteries is 60 and 50 GW. A share of roughly 0,55% is hydrogen and the rest goes to batteries. This percentage is used to calculate the demand for hydrogen in electricity storage demand. This leads to roughly 30 PJ hydrogen electricity storage demand in 2050.
- Vision 2 has also large capacity for offshore wind. The total demand for hydrogen in other sectors than power balancing is larger. The total electricity demand of the COMBO scenario is considered. A similar share of hydrogen can be considered of Gasunie & Tennet (0,55% share). If that number is compared to EC, it could be similar, because pumped hydro is not a solution for the Netherlands and could be replaced by hydrogen. This leads to a demand of roughly 25 PJ hydrogen electricity storage demand in 2050.
- Vision 3 is the full hydrogen future, large interconnection for hydrogen is considered. If this is compared to the international scenario of Gasunie & Tennet, only a very small capacity of storage is installed. It is expected surpluses and shortages of electricity/energy are traded between countries, therefore it is expected the demand for hydrogen as storage capacity is 0.

Calculations on industry are based on the values found of DNV GL (2017b), BlueTerra (2018) & CE Delft (2015).

Industrial data				Included in vision		
	Value	**Unit**	**Source**	**1**	**2**	**3**
Total hydrogen demand	100	PJ	DNV GL, ECN etc.	x	x	X
Heat demand total 2050	386	PJ	Blue terra			
<100 °C 2050	42,10909	PJ				
100-250 °C 2050	57,9	PJ				X
250-500 °C 2050	85,97273	PJ				X
>500 °C 2050	200,0182	PJ			x	X

Calculations on transport predictions for 2050 are calculated on data from CBS, PBL, RIVM, & WUR, (2018) with changes to 2050 of the European Commission (2018).

Transportation						
	H2 scenario	**Vision 3**	**COMBO**	**Vision 2**	**Unit**	**Source**
Totaal energieverbruik	354,5		349,3		PJ	CBS, PBL, RIVM, & WUR, with EC
Road vehicles	201,6		200,2		PJ	
Passenger vehicles diesel	36,7	X	36,5		PJ	
Light commercial vehicles	30,0	x	29,8		PJ	
Heavy commercial vehicles	42,3	x	42,0	X	PJ	
Inland shipping	25,2	X	25,3	X	PJ	
Shipping					PJ	
Fishing					PJ	
Air transportation	11,4	X	11,5		PJ	
Rail traffic	1,7	x	1,8	x	PJ	
Mobile tools					PJ	

Calculations on built environment are based on heat demand predictions for 2050 of CPB & PBL (2016). The decentral scenario has formed the basis. The demand in 2050 for heat is 145 PJ. Vision 2 includes 5% and vision 3 includes 20%.

Appendix XI – Calculations pathways

Vision 1

Costs for electrolysis:

		Costs high					Costs low				
	Additional capacity in 2020	CAPEX Euro/kW	Efficiency	Additional capacity with improvements GW	Total capacity GW	Costs in millions	CAPEX Euro/kW	Efficiency	Additional capacity with improvements GW	Total capacity GW	Costs in millions
2020	0	1000	64%	0,0	0,0	0,0	1000	64%		0	0,0
2025	0,5	850	67%	0,5	0,5	441,8	850	69%	0,5	0,5	394,2
2030	1	700	69%	0,9	1,4	718,8	600	73%	0,9	1,3	526,0
2035	1,5	675	71%	1,4	2,8	929,6	450	77%	1,2	2,6	561,0
2040	2	650	72%	1,8	4,5	1177,8	350	80%	1,6	4,2	560,0
2045	3	625	73%	2,6	7,2	1676,7	313	80%	2,4	6,6	750,0
2050	3,5	600	74%	3,0	10,2	1854,1	275	81%	2,8	9,4	760,5

Vision 2

Costs for electrolysis:

		Costs high					Costs low				
Year	Additional capacity	CAPEX Euro/kW	Efficiency	Additional capacity with improvements GW	Total capacity GW	Costs in millions	CAPEX Euro/kW	Efficiency	Additional capacity with improvements GW	Total capacity GW	Costs in millions
2020	0	1000	65%	0	0	0	1000	65%	0	0	0
2025	0,5	812,5	68%	0,5	0,5	433,1	750	70%	0,5	0,5	406,3
2030	1,5	625	71%	1,4	1,9	987,0	500	75%	1,3	1,8	812,5
2035	2	581,25	75%	1,7	3,6	1045,4	350	80%	1,6	3,4	690,6
2040	3,5	537,5	77%	3,0	6,5	1652,7	312,5	80%	2,8	6,2	942,0
2045	5	493,75	79%	4,1	10,7	2121,2	275	81%	4,0	10,2	1178,6
2050	7,5	450	80%	6,1	16,7	3539,1	237,5	81%	6,0	16,3	1542,2

Costs for SMR with CCS

			Costs low					Costs high				
Year	CCS units GW	SMR with CCS GW	CAPEX in euro/kW	Share CCS	CAPEX CCS	Costs in millions SMR, CCS	Costs in millions	CAPEX in euro/kW	Share CCS	CAPEX CCS	Costs in millions CCS	Costs in millions SMR, CCS
2020	0	0	1087,0	31%	337,0	0,0	0,0	1388,9	46%	638,9	0,0	0,0
2025	1	0	1027,4	27%	277,4	307,2	0,0	1239,7	40%	489,7	564,3	0,0
2030	1,7	2	974,0	23%	224,0	426,2	2001,4	1119,4	33%	369,4	730,2	2359,1
2035	0	2	937,5	20%	0,0	0,0	1911,5	1102,9	32%	352,9	0,0	2222,3
2040	0	2	937,5	20%	0,0	0,0	1875,0	1087,0	31%	337,0	0,0	2189,9
2045	0	0			0,0	0,0	0,0	1071,4	30%	321,4	0,0	0,0
2050	0	0			0,0	0,0	0,0	1056,3	29%	306,3	0,0	0,0

Vision 3

Costs for electrolysis:

		Costs low					Costs high				
Year	Additional capacity GW	CAPEX Euro/kW	Efficiency	Additional capacity with improvements GW	Total capacity GW	Costs in millions	CAPEX Euro/kW	Efficiency	Additional capacity with improvements GW	Total capacity GW	Costs in millions
2020	0	1000	65%	0,0	0,0	0,0	1000	65%		0,0	
2025	1,5	675	75%	1,3	1,3	1088,8	700	68%	1,4	1,4	1003,7
2030	2,5	350	80%	2,0	3,3	1041,0	450	71%	2,3	3,7	1029,9
2035	5	312,5	80%	4,1	7,4	1345,7	387,5	74%	4,4	8,1	1701,9
2040	5	275	81%	4,0	11,4	1178,6	325	77%	4,2	12,3	1371,8
2045	7,5	237,5	81%	6,0	17,4	1542,2	262,5	79%	6,2	18,5	1619,9
2050	7,5	200	82%	5,9	23,4	1300,5	200	80%	6,1	24,6	1218,8

Costs for SMR

			Costs low	Costs high				Costs low	Costs high			
Year	CCS units GW	SMR with CCS GW	CAPEX in euro/kW	Share CCS	Year	CCS units GW	SMR with CCS GW	CAPEX in euro/kW	Share CCS	Year	CCS units GW	SMR with CCS GW
2020	0	0	1087,0	31%	337,0	0,0	0,0	1388,9	46%	638,9	0,0	0,0
2025	2,7	2,5	1027,4	27%	277,4	829,4	2642,9	1239,7	40%	489,7	1523,6	3099,2
2030	0	2,5	974,0	23%	224,0	0,0	2501,8	1119,4	33%	369,4	0	2948,8
2035	0	2,5	937,5	20%	0,0	0,0	2389,4	1102,9	32%	352,9	0	2777,9
2040	0	2	937,5	20%	0,0	0,0	0,0	1087,0	31%	337,0	0	0,0
2045	0	0			0,0	0,0	0,0	1071,4	30%	321,4	0	0,0
2050	0	0			0,0	0,0	0,0	1056,3	29%	306,3	0	0,0