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Research Paper

Visions for hydrogen in the Netherlands by 2050

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Abstract

Hydrogen is seen as a potential energy carrier in the Netherlands by 2050. To what extent hydrogen will be implemented is unknown, because many applications are possible. Therefore, a backcasting study is conducted. In the situation of hydrogen in the Netherlands, many studies have been conducted on potential visions and scenarios. A different approach is chosen to construct new visions, namely vision comparison of existing studies. The vision comparison is incorporated in participatory backcasting. The vision comparison compares studies based on PESTLE-indicators. The final PESTLE-analysis provides a starting point of a morphological chart to select elements for the visions. The visions are described in a normative description. From the study, the balance between electrons and molecules was often discussed. Thus, the three visions differ in levels of electrons and molecules integration. Vision 1 All electric is based on a system where electrification plays a large role. Hydrogen is used for storage and power balancing. Vision 2 One integrated system is based on both hydrogen and electricity integration. Hydrogen is only applied in some sectors. Vision 3 Go hydrogen is based on full support and development of hydrogen technologies. In every sector and application hydrogen shows potential, it is integrated. From the visions it can be concluded vision comparison is an effective way to construct visions. The approach should be further developed and applied on more studies to determine whether it could be used in more situations. Comparison with workshops could provide insights on what approach works best.

Keywords: Backcasting; Participatory; Hydrogen; Visions; Vision comparison; PESTLE

1 Introduction

In the 2019 published Climate Agreement, the Netherlands set the goal to reduce greenhouse gas emission by 95% in 2050 compared to 1990 (Rijksoverheid, 2019). The Netherlands is known for its process industry, geographical location and experience with natural gas infrastructure. Those three elements offer an opportunity with hydrogen to start a transition towards a clean-tech-industry and to create a knowledge position. The Dutch government describes several functions for hydrogen in the energy system, i.e. (1) carbon free feedstock for process industry, (2) carbon free energy carrier for high-temperature heating in process industry, (3) flexible carbon free power, long-term energy storage, and energy transport over long distance, (4) mobility, and (5) various applications in built environment. To what extent hydrogen will play a role in the future energy system is not elaborated on.

This paper describes three potential visions for hydrogen in the Netherlands by 2050. A backcasting approach is used to describe possible futures. The emphasis of the research is on a normative approach to focus on a certain future situation and how that can be reached (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). Backcasting is a form of normative scenario used when goals are unreachable with the current developments. Backcasting is seen as useful 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). Quist (2007) framework of participatory backcasting forms the basis of this research. The approach is often used for situation where no clear visions for future systems are described. The second step in Quist's framework is the construction of visions with workshops and actor involvement to set the scope for possibilities of future visions. In case of hydrogen, a large variety of visions has been constructed and the possibilities are described. Thus, a different approach is used where existing visions and scenarios are compared. The comparison forms the basis of further vision construction. This paper describes and discusses the approach and methodology for vision construction with vision comparison instead of participatory vision construction.

Section 2 outlines the approach to compare visions for vision selection. Section 3 describes the methodology for visions comparison, selection and construction. Section 4 provides the results of vision comparison, section 5 describes the selection process for the visions, and section 56 the three visions that are constructed in this research. Section 7 discusses the results of this research and the vision comparison approach in backcasting studies. Section 8 concludes by discussing the outline of the visions of the vision comparison approach.

2 Approach to compare visions for vision selection

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 based on current events, backcasting allows to explore desirable futures, where major adjustments are needed. 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). Many approaches have been designed in backcasting literature. Four backcasting approaches are broadly discussed in literature, i.e. 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), and Participatory backcasting (Jaco Quist, 2007).

Quist's participatory backcasting is used as a basis for this study. Three key elements of participatory backcasting can be selected (J Quist, 2013; Jaco Quist, 2016): construction and use of desirable future visions or normative scenarios, strong stakeholder involvement integrated with stakeholder learning processes, and using a wide range of methods: process, participation, analysis and design. Those elements have led to a five-step approach of participatory backcasting. The approach up to step 2 is used in this research. 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).

The participatory methods, such as workshops and interviews, are used in situation where visions are lacking. In case of hydrogen in the Netherlands, many studies have been conducted on the potential of hydrogen by 2050 (Table 1). Instead comparison and selection techniques are necessary to construct visions in step 2.

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, de Groot, van Paassen, Park Lee, & Regett, 2013). PESTE takes five aspects in consideration: Political, Economic, Social, Technical and Environmental. Legal elements can be included when needed. Visions can be analysed on those aspects and allow for consistent comparison. A systematic approach in comparing visions enables clustering visons and highlighting differences. Furthermore, a quantitative analysis of the studies can be used to find differences in vision outcomes.

3 Methodology for vision comparison and construction

The development of three visions for hydrogen in the Netherlands has been based on a three-step process with step 1: vision comparison, step 2: vision construction, and step 3: vision description. The three steps lead to three visions for hydrogen in the Netherlands.

Report	Reference	Title	Focus year	Scope
Platform Nieuw Gas	(Platform Nieuw Gas - werkgroep Waterstof, 2006)	Waterstof Brandstof voor transities	2050	The Netherlands
Hisschemöller	(Hisschemöller, Bode, van de Kerkhof, & Stam, 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, Graafland, & Warnaars, 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 (FCH) Joint Undertaking	(FCH, 2019)	Hydrogen Roadmap Europe	2050	Europe
Provincie Zuid-Holland	(Wijk, Rhee, Reijerkerk, Hellinga, & Lucas, 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

Table 1 - Overview visions for vision comparison

Studies and reports on hydrogen in the Netherlands have been selected (Table 1). The selected studies focus on Europe, the Netherlands or regions of the Netherlands. Step 1: Vision comparison follows a three-step process:

(1) Identify PESTLE-elements of existing visions;
(2) Conduct quantitative analysis of exiting visions;
(3) Specify PESTLE-elements for hydrogen visions.

The result of step 1 is an overview of elements that can be used for step 2: Vision construction. Step 2: construction follows a five-step process based on a morphological analysis (Ritchey, 2014):

(1) Identify extremes in visions;
(2) Define parameters visions;
(3) Assign relevant conditions to parameters;
(4) Select conditions for each parameter
(5) Check cross-consistency for selected conditions.

The results of step 2 lead to the outline of the three visions. Step 3: Vision description describes each vision based on three vision elements (McDowall & Eames, 2007):

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

The constructed visions are validated in interviews in a later stage. The visions provide a starting point for further steps in backcasting studies. The interviews and backcasting study are left out of the scope of this paper, because it discusses the use of visions comparison for visions construction.

4 Vision comparison

The visions of Table 1 are analysed. The results are discussed in vision comparison. PESTLE- elements and quantitative results for each were compared. Section **Error! Reference source not found.** provides the quantitative summary of the compared visions. Section 4.2 describes the difference that were found in comparing the visions on PESTLE-elements. Section 4.3 describes the PESTLE-analysis where all results of vision comparisons are combined.

4.1 Quantitative analysis

The reports that have quantitative data are analysed in a quantitative analysis. 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 1. 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. The European Scenarios, European Commission and FCH, are determined for the Netherlands (Visman, 2019). 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.

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.

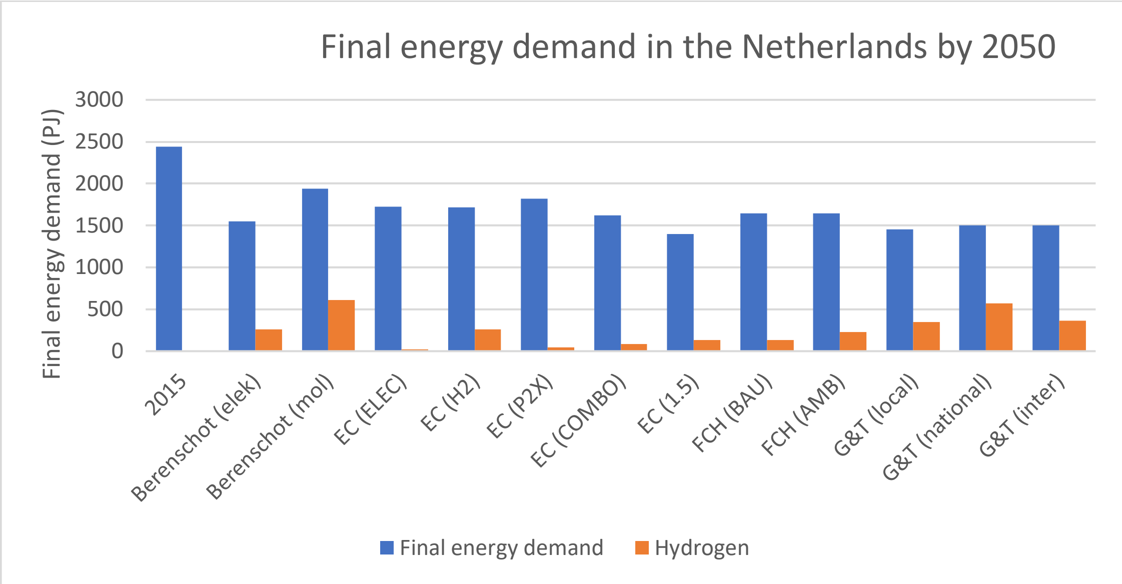

Figure 1 - Final energy demand with share of hydrogen for 2050. European studies are determined for Dutch final energy demand.

The share of hydrogen compared to the final energy demand is shown in Figure 2. 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 identified as shown in Figure 3, 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 1 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.

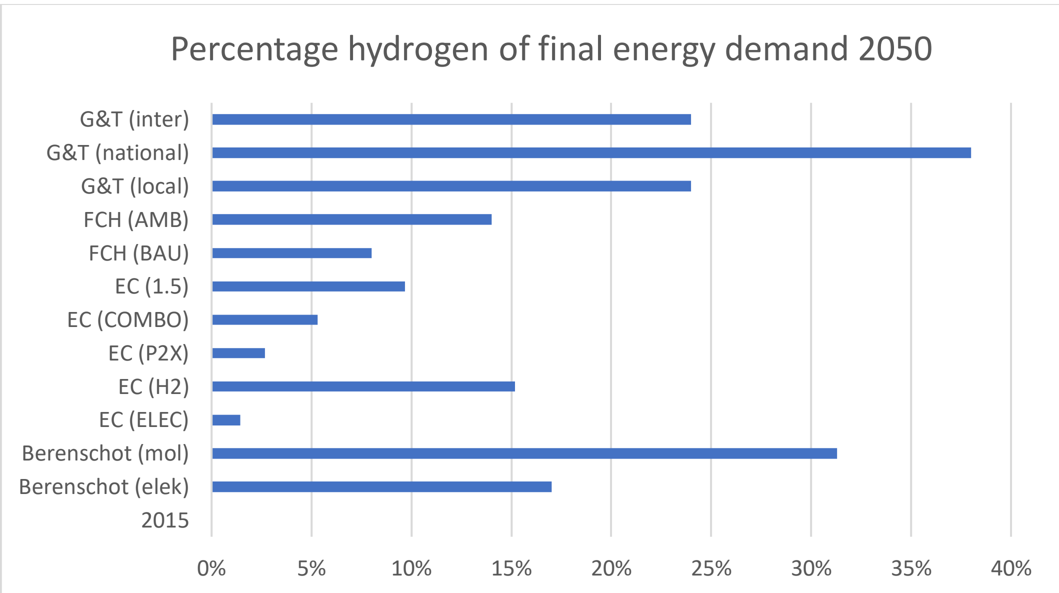

Figure 2 - Share of hydrogen of final energy demand the Netherlands in 2050.

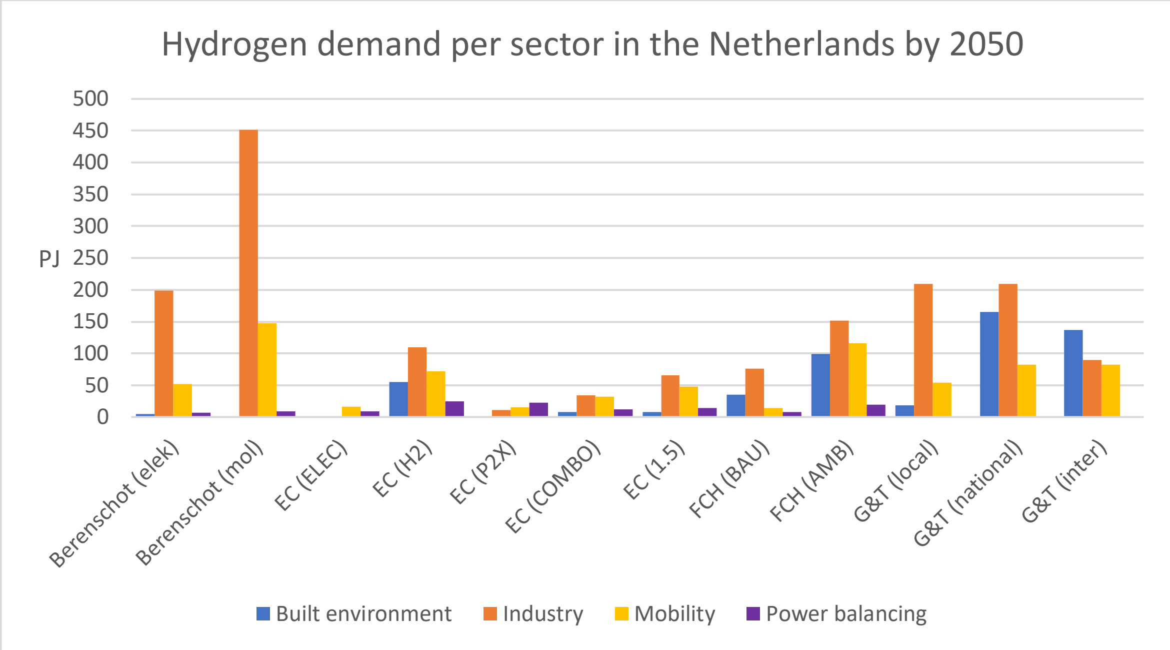

Figure 3 - Hydrogen demand per sector

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.

4.2 Differences in 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 necesary (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.

4.3 PESTLE summary

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 2.

5 Vision construction

As a basis for the vision construction some objectives have been formulated to what the visions should comply. 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 and not region specific.

From the vision comparison, it can be concluded an important indicator for the future of hydrogen is the level of electrification in sectors. Three levels of hydrogen integration have been selected as a basis for the scenarios:

- Vision 1: All electric – electricity is preferred for every application. (hydrogen secondary carrier);
- 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);
- Vision 3: Go hydrogen – emphasizes is placed on hydrogen for end use (hydrogen mainly primary carrier).

Table 2 - 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

5.1 Morphological chart

Vision specific elements are determined with a morphological chart, highlighting PESTLE indicators and market, infrastructure and supply indicators. Key actor involvement is part of the vision description. From the vision comparison and PESTLE analysis of the hydrogen system various components can be selected. shows the morphological chart for possible visions. Based on the three-selected variation in visions, elements can be selected from Table 3 that align with the overarching visions. For each vision elements are selected in the morphological chart that match the first vision description. Table 3 shows element selection for vision 1: All electric. All components are checked on consistency to make sure a viable vision is designed. The other morphological charts can be found in Appendix 2.

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.

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.

6 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 4.

6.1 Vision 1: Electricity first

Vision 1: All Electric describes a future system for the Netherlands in 2050 where electricity is seen as the holy grail for the energy transition as shown in Figure 4.

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. Electrification is reached in all applications where possible. Since decarbonizing industry with solely electricity is challenging, hydrogen plays a role in this market. 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. Thus, hydrogen is used in power plants. Storage of hydrogen takes place in salt caverns.

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 3 - Morphological chart with selections for vision 1: All electric

Table 4 - Quantitative summary of visions (Visman, 2019)

	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.

6.2 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 5.

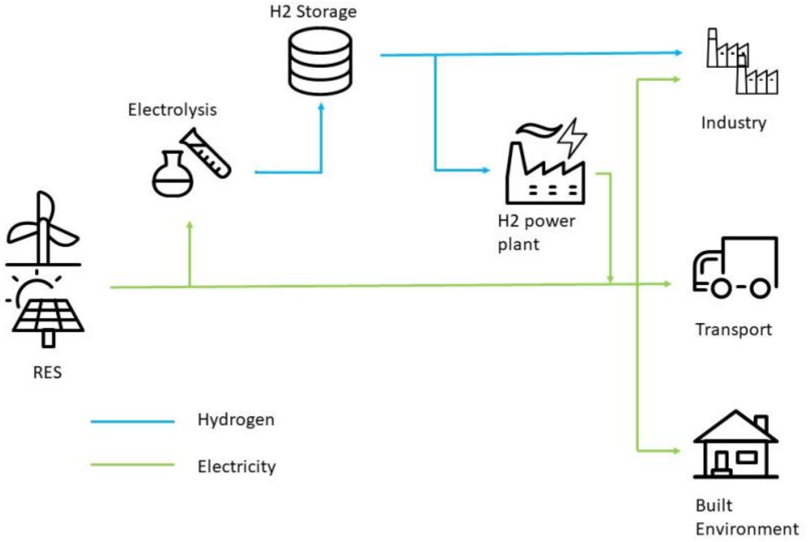

Figure 4 - Hydrogen system vision 1

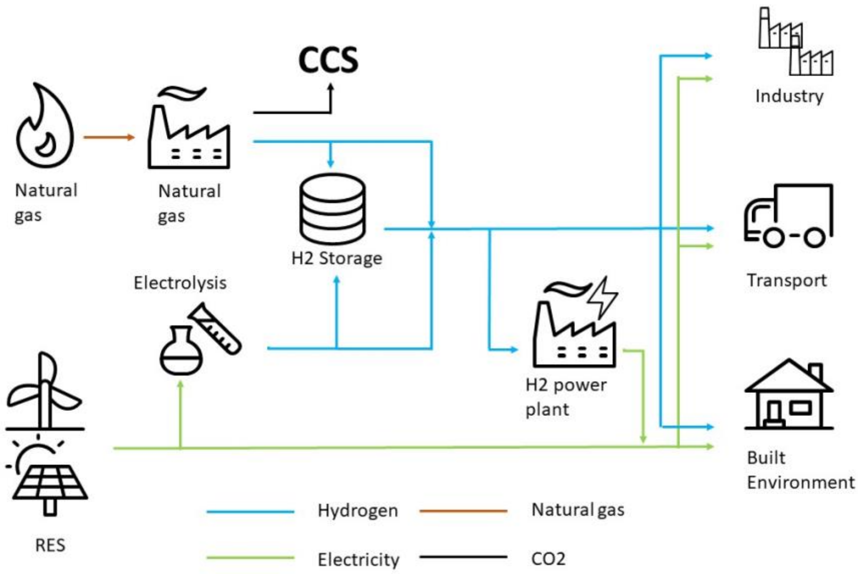

Figure 5 - Hydrogen system vision 2

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. As a solution blue hydrogen is used as an alternative.

6.3 Vision 3: Go hydrogen

Vision 3: Go Hydrogen represents a system where hydrogen is exploited to its full potential as shown in Figure 6.

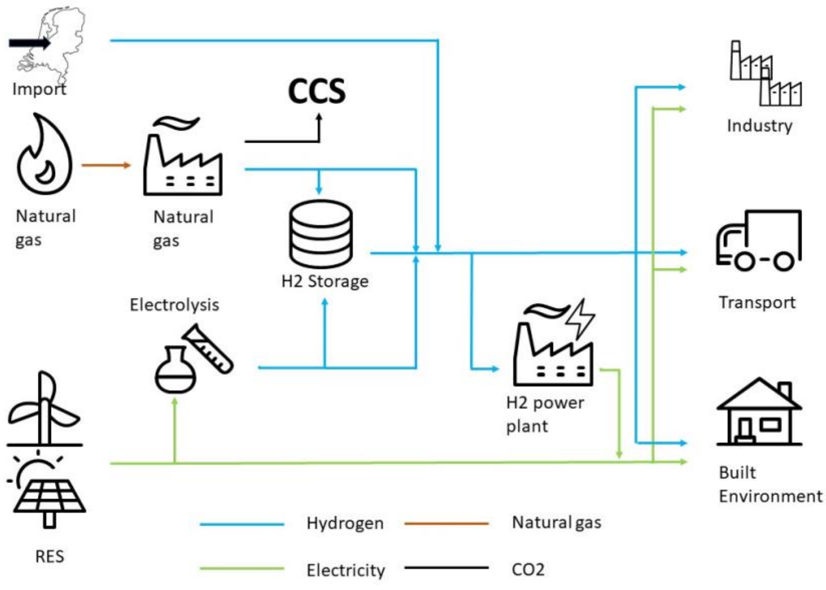

Figure 6 - Hydrogen system vision 3

Full political 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. 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.

7 Discussion

The vision comparison is a method that is different from other backcasting studies. The methodology of PESTLE has proven relevant to set the scope of vision options. 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.

Comparing the constructed visions to Navigant (2019) and KIVI (2017). The Navigant study has a total energy demand for hydrogen of 6156 PJ for the EU. From the demand most is reserved for power balancing and industry (roughly 45% and 39%). Only a small share goes 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). Mobility overlaps with the demand in vision 3, while the demand in industry comes closer to vision 2. Especially the study of Navigant could have influenced the outcomes in vision 1 on power balancing with hydrogen.

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. Delpierre 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 of focus on electricity, focus on hydrogen or a combination of the two. The differences between the study of Delpierre and this thesis are mainly caused on the scope of the visions and the reason why they are constructed.

8 Conclusion

The backcasting study has led to three visions for hydrogen in the Netherlands by 2050. The three visions are:

- Vision 1: All electric – electricity is preferred for every application. (hydrogen secondary carrier);
- 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);
- Vision 3: Go hydrogen – emphasizes is placed on hydrogen for end use (hydrogen mainly primary carrier).

Different from other participatory backcasting studies, existing visions and scenarios are used to construct the visions. The approach has led to varying visions with different outcomes for hydrogen, all challenging to implement. Though it may seem backcasting is not necessary in a field where many visions are known, regarding the energy transition, many different pathways are possible and backcasting may lead to different scenarios.

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.

For further research, the approach should be further developed. To see what the difference is between vision comparison and workshops, both could be conducted on one topic. Furthermore, modelling could be combined with the selected visions to research the dynamics between existing visions, an energy model and following steps of backcasting.

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Appendix 1 – PESTLE visions

	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 CO2 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 CO2 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 2 – Morphological charts vison 2&3

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						