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Analysis of the hydrogen transition in the Netherlands using Strategic Niche Management and Event Sequence Analysis

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Summary

The Netherlands aims for a Fossil-Carbon-free, sustainable, and circular economy by 2050 (Ministerie van Economische zaken, 2016). This aim fits in with the broader efforts of the international community, as laid down in the Paris Climate Agreement, to limit the effects of climate change (UNFCC, 2015). Such a far-reaching transition to a fossil-carbon-free, green energy supply and economy requires a different approach to fulfilling the energy demand. A drastic change in the energy system of this order simply cannot be achieved with small steps but requires a radically different way of thinking and cooperation between relevant stakeholders.

Hydrogen is increasingly being considered worldwide as an all-encompassing energy carrier to reach the climate goals and simultaneously promote economic vitality (see Section 2.1). The Dutch government, specifically, has been pursuing the energy carrier through the simultaneous implementation within four different sectors (industry, electricity, built environment and mobility), and has emphasized an all-encompassing approach with collaboration between different actors (Government of the Netherlands, 2019). Therefore, this thesis is an analysis of this emerging hydrogen transition in the Netherlands, with the aim to uncover how the implementation of hydrogen has gone and how it can be facilitated in the future.

The theoretical approach towards studying sustainability transitions have been formed most formidably by the body of research on socio-technical transitions (Rotmans, etal., 2001; Brown, et al., 2004; Loorbach, 2007; Geels, 2010; Smith, et al., 2010). The most prominent model that has emerged, the Multi-Level Perspective (MLP), argues that for a socio-technical transition to be successful, a rooted, prevailing regime must undergo synergistic pressures from three different levels (Landscape, Regime and Niche) (Geels 2005a, b; Genus and Coles 2008). For this thesis, the MLP has been merged with the governance approach Strategic Niche Management (SNM) (Schot & Geels, 2007), which focuses on the implementation of niches, which have a crucial function to destabilize and disarrange established regimes.

From these merged theories, criteria stemming mainly from the v.d. Laak (2007) were used to analyse the implementation of hydrogen niches. These criteria put a theoretical emphasis on small-scale experimentation with a focus on assessing the quality of three internal niche processes (Voicing of Expectations, Network Building and Learning Processes) that re-enforce and influence each other. The criteria state that expectations should be supported by an increasing number of actors, they should become clearer and more specific and they should be supported by sufficient evidence over time. The actor network should increase in diversity and alignment due to successive experimentation. Lastly, more data should be assimilated (through experimentation) to further optimize implementation (first-order learning) and actors should show enough flexibility to modify their underlying assumption regarding the niche over time, when faced with supporting evidence (second-order learning).

Due to the complexity of hydrogen as an energy carrier, mainly attributed to its multiple production methods and applications within four different sectors, analysis of the hydrogen transition pathway becomes difficult. Therefore, in spite of its emerging nature the energy carrier has not been comprehensively considered within the sustainability transitions literature; the traditional use of transitions theory has methodological shortcomings, due to its embeddedness within the multivariate perspective (with interviews as primary data), that inhibits the study of such a comprehensive transition across a long time-span, due to its focus on momentary snapshot within singular domains. Because of this, it was necessary to merge the theory with a methodological approach previously never used together, which enables examination of the entire transition with detailed analysis of how it has developed over time.

The approach that was used, 'Event Sequence Analysis' (ESA) stems from the process perspective, which views reality as a 'stream of events' without the need for "stable entities". ESA has provided specific rigorous tools and a data collection process that allowed for the analysis of the entire hydrogen transition from a long-term historical perspective, through assessment of linkages between the most relevant events and visualization of these in a so-called "event map". Due to the focus on linkages and the visualization tool, it has become possible to analyze the implementation of different hydrogen niches within all four relevant sectors and how they affect the transition pathway across sectors. Through the merging of the ESA methodology with criteria stemming from SNM (and MLP), the progress of the hydrogen niches could be analyzed across two decades (2000 – 2020). Because primary data collection is done through historical database searches, instead of interviews, it has become possible to cross-reference data that spans back decades, nevertheless, this also makes ESA quite data-intensive.

From the Event Sequence Analysis, it has become clear that Landscape events have been highly influential in moving the niche implementation forwards by applying top-down destabilizing pressure on the regime. These landscape shifts can roughly be split into two different periods, which showcase distinct characteristics.

- **2000 – 2013: Movement towards less dependence on OPEC & starting Climate movement**
  The first period (2000 – 2013) was initiated by the 9/11 attacks in the US in 2001, which essentially sparked the entire modern hydrogen transition towards its potential as an all-encompassing energy carrier that could conceivably make the western world more independent from OPEC, with the US president coining it the "freedom Fuel" in 2003. The US' investment in the fuel directly led to an increase of attention towards the energy carrier in Europe (and the Netherlands), which sparked an initial development of the hydrogen niche in the Netherlands between 2000 and 2008, with practical experimentation mostly in the mobility sector and some feasibility studies in the Energy and Industry sectors. In 2008, in the aftermath of the economic crisis, the expectation arose that the niche was too expensive and underdeveloped, causing a kind of wave movement with fluctuations in subsidy flows, which stopped most of the experimentation between 2009 and 2012.
- **2013 – 2020: Climate Change Movement**
  The second period (2013 – 2020) is characterized by the climate movement, with multiple landscape events that directly led to more hydrogen uptake in all of the relevant sectors. The increased climate pressure, first from the SER accord (2013), then from the Paris Climate Agreement (2015) and towards the Dutch draft climate agreement (2019) has led to multiple openings due to the pressure on the established Oil and Gas regime. Furthermore, the energy transition also saw the rise of influential parallel niches, most notably, the Dutch opting for off-shore wind as a main renewable energy source, which combines well with hydrogen. Due to these openings, while still moderate, this period saw an increase in practical experimentation, with the most in-field projects in the mobility sector and a plethora of feasibility studies and plans in the energy and industry sector.

While the practical experimentation has been limited, the internal niche processes can be considered of high quality, which has led the country to be one of the front-runners worldwide. It is mostly due to the large-scale nature and financial barriers that this experimentation has been moderate. Due to the country's early and clear voicing of positive expectations, especially in the Northern Netherlands (which is most affected by the landscape pressure on the gas regime), the country has positioned itself as a European hydrogen hub. This positioning is a consequence of early experimentation, leading back to 2003, with high-quality learning processes that have been integrated in successive events and due to a broad actor network with diverse stakeholders that are open to collaboration and are involved in multiple projects across the country in large consortia. This lateral sharing of information not only extends across inter-sector projects, but also crosses among the different sectors, leading to more optimized implementation.

Despite the high-quality internal niche processes across the board, implementation has been moderate due to the financial barriers that comes with it, which can be attributed to the sheer expense of projects due to the niches' infancy, the large-scale nature of the transition, with the infrastructural overhaul that needs to take place and some current legislative limitations, such as sub-optimal directives towards hydrogen-grid mixing. Furthermore, there are still some pivotal misalignments in expectations between the government and industrial parties surrounding the amount and type of subsidy that should be awarded to blue- and green hydrogen projects. Furthermore, there is still some regulatory unclarity which is causing internal misalignments between actors, which in turn is causing actors to be hesitant to become involved with the niche. Finally, due to a lack of experimentation, learning processes are still in an early phase and need improvement.

So, from the ESA analysis it can be observed that there is clear connection between the three different levels of the MLP; throughout the event descriptions, there are instances of windows of opportunities directly stem from a regime internal pressure (e.g. the oil and gas market instabilities), which caused an opening for Nuon's H2Magnum project. Next to this, there are three apparent patterns that can be identified: (1) A clear succession of niches, (2) a dependence on international collaboration and (3) regional embedding (cluster formation).

1. **Succession of Niches**
   The first clear pattern that follows from the ESA is that there are clear links between successive events. This has been successfully linked to the SNM theory with the general conclusion that the hydrogen niche has performed exceptionally from an internal niche perspective. Successive projects have perpetually been influenced by positive expectations stemming from previous success stories or are facilitated by previously established collaboration. Furthermore, there are lateral links between projects, which makes it possible for learning processes to the implemented in successive events, which further optimized implementation. This good niche performance (in addition to landscape and regime influences, as well as favorable conditions), has led the Netherlands – especially North-Netherlands – to be one of the frontrunners when it comes to hydrogen implementation.

2. **International Collaboration**
   Another emerging pattern has been the clear dependence on international collaboration. Particularly within the mobility sector, most niche implementations are embedded within international (mostly European) initiatives and projects or have been subsidized by them. While it is most apparent in the mobility sector, this can be attributed to the fact that this is the sector where most in-field projects have emerged. This dependence can also be observed in the Energy and Industry sectors, where the most influential developments, e.g. the construction of the first electrolyser (HyStock) or the Northern Netherlands' position as European hydrogen hub, have been influenced tremendously by European influence (particularly in the form of subsidies).

3. **Cluster formation (regional embedding)**
   A final pattern is the regional embedding of the implementation of most of the niches. This can be attributed to the large-scale nature of the transition and the dependence on synergistic implementations with dependence on supply to multiple sectors. Therefore, it is most apparent in the Energy and Industry sectors, with a focus on implementations with the Northern Netherlands and South-Holland, with the benefits that come along with their big industrial clusters situated near the harbor. The unique selling point for the Northern Netherlands cluster stemmed from the proximity of all the onshore and offshore gas fields and in the South-Holland cluster the presence of the port of Rotterdam was a plus for sales opportunities for CO_2 by ship. Within these clusters is where most of the Energy sector and Industry sector activities arise.

To conclude, from the ESA it has become clear that the hydrogen transition is complex and needs active stimulation to become adopted more widely. Major challenges stem from financial barriers, which are attributed to the large-scale nature of the transition, as well as a sub-optimal policy framework and the need for additional flanking activities. The ESA analysis has showed that (practical) niche experimentation has moved along the transition most rapidly, through first-order learning, by the uncovering of new unsolved questions, what the optimal policy framework would be and second-order learning, which showed entirely new application possibilities, which were previously undiscovered. Due to the infancy of the hydrogen transition, the further adoption of the energy carrier in the Netherlands in all relevant sectors should be stimulated by the continued niche implementation and upscaling. So, the upscaling should be pursued with three main aspects in mind. (1) Firstly, it should be done within embedded regions, which are mainly formed in (harbor) clusters. (2) Secondly, the ESA proved that international collaboration is of essence in this transition. (3) Lastly, there should initially be a concrete focus on knowledge creation, due to the complexity of the transition, there is still a lack of knowledge with regard to the optimal implementation and a lack of educated personnel, which will all be pivotal for the success of this transition.

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Chapter 1

Research Introduction

In 2014, the Intergovernmental Panel on Climate Change (IPCC) reported being more than 95% confident that global warming is caused by anthropogenic drivers, such as greenhouse gas emissions (IPCC, 2014). The consumption of fossil fuel causes an increase in CO_2-emissions, which is not in line with the Paris Agreement and causes environmental issues. In order to combat this, the energy sector needs to be decarbonized. This can be done by introducing emission free energy carriers into the energy mix. One of the most prominent sustainable energy carriers is Hydrogen, since it is the simplest element known to man and most plentiful gas in the universe and hydrogen made with renewable energy is completely CO_2-free. If it is used to generate electricity, clean water is the only emission. Hydrogen is also easy to store and transport. Its storage capability makes it a good complement to intermittent renewable energy sources.

Before hydrogen becomes a significant fuel in the Netherlands' energy picture, many new systems must be built. We will need systems to produce hydrogen efficiently and to store and move it safely. Even though the Netherlands has the benefit of having gas pipelines, they need to be proven to be safe. Additionally, fuel cells need to become more economical and consumers will need the technology and the education to be able to use it. With advancements in fuel cells and other technologies, hydrogen has the potential to provide a large amount of clean, renewable energy in the future. Aside from technical feasibility, when assessing the implementation of a different technological solution to a social issue, human behavior change plays a huge role in its success; both in terms of producers and consumers (Kemp, Schot, & Hoogma, 1998). In an increasingly interconnected society, the success of an innovation depends on changes up and down the value chain and on numerous social processes in which multiple actors from society, government, science and industry interact. So, the challenges are enormous, and they are not only technological and economic, but also organizational and administrative, and even cultural-social in nature. Studies show that due to the multifaceted nature of the molecule, collaboration is essential to successfully deploy hydrogen. Additionally, investments are pivotal, and uncertainties still exist regarding the risks and consequences for users and citizens.

The focus of this thesis will be on the overall Dutch hydrogen transition and all facets that it has been influenced by and simultaneously influences. Due to the complexity and infancy of the hydrogen transition, it will affect every level of the Dutch society (Landscape, Regime and Niche) and a plethora of actors in different sectors (industry, electricity, built environment and mobility). The Hydrogen transition is unique, as opposed to e.g., renewable energy technologies (like solar PV or Wind), since it has different end-uses and is not inherently sustainable; hence it deals with the explicit goal of sustainable development by fostering the transition to a (all-encompassing) hydrogen economy. An explicit focus is placed on hydrogen clusters: clusters that specialize in the various fields of the hydrogen economy and that are expected to play a key role in its development. In general, cluster initiatives have become an important tool for governments to establish, promote, and strengthen economic collaboration, learning, innovations, and employment within a certain region.

The **Problem** is how the energy transition should be approached and what the role of hydrogen is in such a transition. Especially in the Netherlands there is a double urgency since the 'Gaskraan' will be closed soon. This means that the fossil-based economy is experiencing severe pressure and kilometers of gas pipelines will be rendered obsolete if an alternative is not found. Furthermore, hydrogen implementation is complex and there is a lack of research on how the implementation of hydrogen is going in the Netherlands; whether it is going according to plan or course correction is needed. The **desired situation** is for the Netherlands to become independent from fossil fuels in an economically sustainable way, while maintaining security of energy supply in the long term. This has implications for all sectors, incl. heating in built environment, transport and industry.

To clearly understand why this research is relevant, first the necessity for a hydrogen transition in the Netherlands will be elaborated upon. Furthermore, the current theoretical shortcomings to research such a complex Socio-Technical transition with will be discussed and it will be argued that there needs to be theoretical elaboration. This is followed by the research question that stems from this, followed by the societal relevance, after which the outline of this thesis is briefly presented.

1.1 Necessity for a study of the emerging Dutch hydrogen transition

The Netherlands aims for a Fossil-Carbon-free, sustainable, and circular economy by 2050 (Ministerie van Economische Zaken, 2016). This aim fits in with the broader efforts of the international community, as laid down in the Paris Climate Agreement, to limit the effects of climate change (UNFCCC, 2015). Such a far-reaching transition to a fossil-carbon-free, green energy supply and economy requires a different approach to fulfilling the energy demand. A drastic change in the energy system of this order simply cannot be achieved with small steps but requires a radically different way of thinking and cooperation between relevant stakeholders. A transition to a sustainable energy system and a circular and sustainable industry is necessary in order to achieve a society that will be (almost) entirely CO_2 neutral in 2050. The emissions released from the use of energy and raw materials must, therefore, be drastically reduced. Production, transport, and storage must also be emission-free within such a system. For this, emission-free energy carriers are absolutely required. Green (CO_2-neutral) hydrogen makes the energy transition possible for the chemical industry, mobility, and electricity. Next to helping achieve the climate goals, it can also strengthen the economy.

This is necessary, because the Netherlands has a double urgency for the development of a green hydrogen economy: a new economy and sustainability. At present, the economy of Zuid-Holland, with the Harbour Industrial Complex (HIC), the strong (Petro) chemical cluster, the unique logistics hub, and greenhouse horticulture, is mainly built on fossil energy. The Northern Netherlands also deals with a double urgency, in addition to the switch to sustainable energy supply, gas production must also be greatly reduced due to the earthquakes caused by gas extraction. The draft climate agreement confirms the role of hydrogen in sustainable energy supply and aims to arrive at an integrated hydrogen policy. Such a program will consist of a national component when it comes to the realization of the necessary preconditions, but also of regional sub-programs with a customized approach per industry cluster and surrounding area. This requires cooperation between key parties (governments, market parties, knowledge institutions, network companies, and social organizations) so that the development of a hydrogen system can take a coordinated form.

1.1.1 Research gap related to the emerging hydrogen transition

On a regional level, provinces do not have to wait for an overall hydrogen policy. They can bring parties together within their own possibilities and policy frameworks (including spatial planning, infrastructure, use of financial instruments and emission standards, purchasing, public transport concessions, granting permits) and draw up an action plan for hydrogen. It is up to the provinces and clusters themselves to operate externally proactive and initiating. The problem is that such a transition is very complex and it is not predefined how to approach it. Hence it is of utmost importance to research how a transition to new energy carriers should be dealt with and how this can be facilitated in the future. Hydrogen will play an important role in the Dutch energy transition, as can be seen in the Dutch Energy Agenda (Ministry of Economic Affairs and Climate Policy, 2016). There are already many (individual) smaller initiatives, the number of which is only growing. In order to initiate a system change, strong long-term commitment is required on the part of the business community, the industry, and the government with contributions from knowledge institutions and social organizations (Gigler & Weeda, 2018). It is of great importance that these smaller initiatives are being implemented properly. Additionally, large industry clusters are forming, particularly around the Rotterdam harbor (South Holland Cluster) and the Eemshaven (Northern Netherlands Cluster). It is pivotal that these clusters are viable and capable of reaching the 2050 goals.

When it comes to hydrogen, there is a scale jump needed in the short term for cost reduction in technology and infrastructure. It is forecasted that the cost-effective production of emission-free hydrogen will be possible in 2030. This can only be achieved through investments in production clusters of green hydrogen, a production location for blue hydrogen, and the conversion of existing industry. Gasunie and TenneT have modeled the three scenarios developed by Netbeheer Nederland (Afman & Rooijers, 2017) and produced the "Infrastructure Outlook 2050" in which they propose a pathway to an interconnected Gas and Electricity infrastructure, with Power2Gas as a cornerstone to transform excess electricity into hydrogen (Gasunie & Tennet, 2019). The technical feasibility of this has already been the subject of numerous studies (Ministry of Economic Affairs; van der Noort, Vos, & Sloterdijk, 2017; Hermkens et al., 2018). However, for this transition towards hydrogen to be successful, research is required to analyse the (historical) implementation of Niches in the Netherlands to see whether they are able to reach the goals of 2050 and if not, how this can be facilitated in the future. This forms the main motivation behind this research, in which from a (historical) system perspective, the main experiments and the partnerships, organization and regulation around the implementation of Hydrogen has been handled in the Netherlands.

The industry now mainly produces hydrogen locally through fossil raw materials. Except in Chemelot (near Geleen), all major industrial clusters are located on the coast (CBS, 2020). In the future, it is expected that a large amount of wind series will come ashore on the coast. In a recent study - conducted in 2019 - 'Infrastructure Outlook 2050', TenneT and Gasunie have found that it is essential to find a solution for the sorting of this wind energy (Gasunie & Tennet, 2019). According to the study, a solution is a large-scale investment in electrolysis for the production of (green) hydrogen along the coast; the hydrogen then only needs to be transported in-land or to neighboring countries. The assumption is that by 2030, a minimum of 11.5 GW offshore wind power must be fitted into the energy system, which will mainly land close to the coast (ibid.). In order to circumvent losses attributed to the conversion of transport of sustainable energy, it is most cost-efficient to have supply and demand close to each other. Therefore, where possible, it is vital to electrify the industry near the coast. However, electrification will not be an option for all industrial processes, for example, molecules remain necessary for the chemical industry. The various industrial clusters on the coast are, therefore, suitable starting locations for the production and consumption of CO_2-neutral hydrogen. Due to the above-mentioned assumptions, it is currently prognosticated that the infrastructure for hydrogen will initially develop in different coastal clusters - until about 2025 - as has been taken up in the Hydrogen Manifesto and the Climate Agreement (Rijksoverheid, 2019). Concrete concepts have already been devised for this in the Eemshaven and the port of Rotterdam.

1.1.2 Theoretical shortcomings related to the study of the hydrogen transition

Hydrogen is increasingly being considered worldwide as an all-encompassing energy carrier to reach the climate goals and simultaneously promote economic vitality (see Section 2.1). In spite of its emerging nature the energy carrier has not been comprehensively considered within the sustainability transitions literature. The Dutch government, specifically, has been pursuing the energy carrier through the simultaneous implementation within four different sectors (industry, electricity, built environment and mobility), and has emphasized an all-encompassing approach with collaboration between different actors (Government of the Netherlands, 2019). While this more comprehensive view is occurring in practice, consideration of the role of such complex and interwoven (national) development initiatives in scholarship on sustainability transitions has been minimal.

The theoretical approach towards studying sustainability transitions has been formed most formidably by the body of research on socio-technical transitions, which evolved from multiple bodies of study to uncover a framework for comprehension of how shifts in large and complex socio-technical systems develop (Rotmans, et al., 2001; Brown, et al., 2004; Loorbach, 2007; Geels, 2010; Smith, et al., 2010). The most prominent model, the Multi-Level Perspective (MLP), argues that, for a socio-technical transition to be successful, a rooted, prevailing regime (e.g., the fossil fuel-based energy system) must undergo synergistic pressures from three different levels (Landscape, Regime and Niche) (Geels 2005a, b; Genus & Coles 2008), with a theoretical emphasis on the crucial function of innovative, niche technologies to destabilize and disarrange established regimes.

Therefore, within the literature there are also efforts to influence, redesign, or dismantle doiminant contextual conditions (Schot & Geels, 2007; Geels & Schot, 2007; Smith & Raven, 2012; Schot & Geels, 2008). This has led MLP to be developed predominantly within the context of governance approaches stemming from transition theory, like Strategic Niche Management (SNM) (Schot & Geels, 2007), which focuses on the implementation of such disruptive niches. These entrenched frameworks (MLP and SNM) were developed primarily from historical (case study) analysis of preceding transitions embedded in a multivariate perspective, with a focus on specific technological innovations within a confined domain, e.g., transport (Elzen & Wieczorek, 2005; Geels, 2005), energy (Verbong & Geels, 2007), water and waste systems (van der Brugge, et al., 2005), housing (Brown & Vergragt, 2008), and food (Smith, 2006).

As the framework is increasingly utilized to inform and guide emerging transitions toward sustainability, transition studies are confronting the broader and more complex range of factors that facilitate or hold back socio-technical change as it unfolds. While it has up to this point been effective in accentuating the co-evolution of technologies, culture, and other social factors, there is a deficiency in research on more complex energy sources (like hydrogen) which have multiple end-used in multiple domains. The hydrogen transition is particularly complex due to its multi-faceted nature; it is not one specific technology, but proposes a new energy system (hydrogen economy), while striving towards sustainability; its success is predicated on the influx of multiple technologies (into the regime) and end-uses in different domains, where the production is not necessarily sustainable.

While the theoretical approach is mostly adequate to study such a complex transition, the typical methodology associated with the extensive body of case-studies is deemed inadequate for a comprehensive study of the hydrogen transition due to its roots within the multivariate perspective, with a usual focus on one specific domain (e.g., energy or mobility) by studying global snapshots of them (through e.g. in-depth interviews). The hydrogen transition, on the other hand, transcends these domains by having multiple influences on a multiplicity of domains. Considerations of parallel niche development has taken place in the literature (Schot & Geels, 2008), nevertheless, within the hydrogen transition, more emphasis should be on the implementation of different types of implementations within the same niche and how the synergistic effects from different sectoral implementations influence the transition trajectory.

Because of the shortcomings in the transitions theory literature, primarily associated with the methodological deficiencies of studying complex multi-faceted energy carriers, with the challenge of having to assess the implementation of the (hydrogen) niche within different sectors simultaneously, there is a need for a new methodological approach that moves away from the global (historical) snapshots with a focus on singular domains that are traditionally used in transition studies. There is on the other hand a need for a methodology which can view the entire transition (viewing all sectors) retrospectively to uncover the “story line” associated with the implementation of the niche, based on a broad range of sources (instead of mainly interviews). Finally, the hydrogen transition becomes more complex to study from a transition research perspective, due to the observation that there are many regime parties dealing with the hydrogen niche, therefore such a new perspective needs to allow for “unstable entities”. This necessity for a new methodology will be further explored in Chapter 3.

Finally, an additional core reoccurring criticism of MLP is that there is a lack of consideration of the region in which the transition takes place, which causes the guidance to remain abstract and insufficient to comprehend or advance the transition within the context (Smith et al. 2010). Recent transition studies have made advancement in closing this gap, through exploring the role of cities or integrating regional development approaches (Hodson & Marvin, 2010; Deutz & Gibbs, 2008) and papers have introduced space considerations and the benefits of geographic proximity (Truffer, 2008; Coenen, et al., 2010; Spath & Rohracher 2010). Nevertheless, seen the pervasiveness of green energy cluster initiatives and their clear necessity for sustainability planning and regional policy, their role in socio-technical transitions should be explicitly considered. Within the MLP framework, clusters are likely to a space between the niche level and the established regime level, with the simultaneous capacity to accelerate or inhibit regime level change in a non-linear and interactive process (McCauley & Stephens, 2012). Therefore, with the hydrogen-specific and theoretical considerations of the necessity of regional initiatives, in this thesis there will be an extra emphasis on cluster formation.

In summary, there are theoretical limitations that are associated to assessment of the hydrogen transition. Firstly, the hydrogen transition is unique as opposed to other technological innovations due to the multi-faceted nature of the energy carrier, which encompasses multiple technological innovations for different end-uses in different sectors. The multivariate view in which most of the transitions research is embedded, with a focus on historical global snapshots, based on in-depth interviews would be too narrow of a view to encompass the entire hydrogen transition in the Netherlands. There is, therefore, a necessity for a retrospective view of the transition, in which it an emphasis can be placed on the time when pivotal events occur and in which sector. Finally, the hydrogen transition will be focused within industrial clusters, hence a focus should be placed on regional efforts.

1.2 Research Question

In the previous section, it has been laid forth why a hydrogen transition in the Netherlands is necessary and why there are theoretical shortcomings for the analysis of such a complex transition. This section will outline the Research questions that will guide the further research.There are a lot of factors that can play a huge part during regime changes of the magnitude that is required for the transition to a Renewable Energy infrastructure supported by a hydrogen economy. Policy measures alone are not sufficient for the transition. There are social and technological challenges that also play a role. Hence, the main Research Question (RQ) of this paper is formulated as follows:

RQ	*"How has the hydrogen niche been developing in the Netherlands, and how can this be facilitated?"*

This will in turn lead to policy and socio-technical recommendations for the Netherlands. In section 1.2.1 This is further elaborated upon.

1.2.1 Sub Questions

A number of Sub Questions (SQs) support this research question. These SQs are intended to provide a clearer understanding of the underlying components that need to be understood in order to answer the RQ.

In order to research the main question, it is essential to see what the literature reveals on the subject, resulting in the first sub-question (SQ):

SQ 1	*"What are criteria for good hydrogen niche development over time?"*

Answering these questions clarifies the approach and theoretical framework which will be used to provide the basis for the method used to analyse the niche performance. Aside from this it is also imperative to understand the added value of the method that will be used with regards to gaining insights on different aspects of niche implementation, resulting in the next sub-question:

SQ2	*"How can the progress of the hydrogen niches and the emerging transition be studied over time?"*

In order to analyse the patterns of niche implementation, a lot of data is needed on the hydrogen clusters. Data that reveals the 'what's', 'who's' and 'when's' on aspects of hydrogen cluster (niche) performance and the relevant context:

SQ3	*"How did the hydrogen niches and the emerging transition evolve over time?"*

Next a deeper analysis is needed on the manner in which Niche experiments arise within the Netherlands (clusters) and how well they perform from a niche transition perspective:

SQ4	*"What patterns can be identified in the hydrogen niches?"*

After the current current progress is mapped out and understood and niche performance is assessed, recommendations can be made about further improvement. This results in the last sub-question:

SQ5	*"How can the emerging hydrogen transition be stimulated?"*

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

1.3 Societal Relevance

This case is interesting because hydrogen as an energy carrier could be a sustainable solution for several wicked issues of our generation. Problems such as the effect of CO_2 on the environment and the depletion of fossil fuel resources could partly be solved. Besides those problems it is, from an academic point of view, interesting to analyse if the current plans regarding hydrogen implementation in the Netherlands have set the right precedence for large scale implementation. To answer the research question, first the literature review will go in depth into the concepts of the systems innovations approach and transitions within the multi-level perspective (MLP). Then, the methodology section will explain in detail the steps that will be taken to collect and analyse the data that will be used to answer the research question.

1.4 Thesis Outline

The previous chapter has introduced the research and outlined the underlying reasoning for the necessity of the study. In chapter 2, firstly the case-study will be elaborated upon, followed by a theoretical background and exploration. Chapter 3 will explain the methodological approach and conclude with an analysis manual, which combined the findings from chapter 2 and 3, and will be used for the analyses of Chapter 4 and 5. In Chapter 4 the hydrogen transition in the Netherlands will be examined through a mix of the theoretical and methodological approaches (SNM, MLP and ESA), which will conclude in key events and an account of the sector-specific barriers. These findings from Chapter 4 will be elaborated in-depth from an SNM perspective (using the analysis manual from chapter 3) to finally uncover the internal niche barriers. Finally, Chapter 6 will give the explicit conclusions on the research question and will finalize with a discussion.

Chapter 2

Background & Theory

As explained in Chapter 1, the focus of this thesis is on the hydrogen transition in the Netherlands. A big part of this analysis is a focus on hydrogen clusters: clusters that specialize in the various fields of the hydrogen economy and that are expected to play a crucial role in its development. The literature study shows that "cluster initiatives have become an important tool for governments to establish, promote, and strengthen economic collaboration, learning, innovations, and employment within a certain region" (Hermans, 2018). Hydrogen clusters are unique in that they serve a dual purpose, while simultaneously promoting sustainable development, they are nurturing a transition towards a hydrogen economy. The ultimate goal of the hydrogen economy is to replace our current fossil-based sources of carbon with renewable sources of hydrogen. In addition to shifting from a fossil-based economy toward renewable energy, the hydrogen economy wants to contribute to creating new economic opportunities. In a society that is becoming more interconnected, the achievement of such a transition relies upon changes across the whole supply chain and on various social procedures in which stakeholders from different layers of our society - including government, science, industry, business, and consumers - collaborate.

Thus, a successful shift from a fossil-based economy to a hydrogen economy requires a radical reorientation of production and consumption processes. Profound shifts like this are referred to as 'Socio-Technical Transitions' (Rip, Kemp, & Kemp, 1998; F. W. Geels, 2002). This is because they not only concern technological changes, but also social considerations like consumer behavior, policy changes, cultural implications, infrastructure shifts and innovation in business models. For mainstream social sciences, socio-technical transitions to sustainability are challenging because they are multi-actor, long-term, goal-oriented, disruptive, contested, and nonlinear processes. The functioning of technical systems, such as the electricity grid, demands organizational cooperation, in addition to good infrastructure and regulation. Thus, the analysis of such radical innovation processes and fundamental transformations is demanding because the underlying innovation processes are complex as they typically depend on the co-development of new socio-technical configurations new market structures, new actors and new institutions.

In the innovation literature, two major strands of conceptual and empirical work have emerged that address the two perspectives: *Innovation system approaches* and the literature on *Technological transitions*. Innovation systems are composed of networks of actors and institutions that develop, diffuse and use innovations (Carlsson & Stankiewicz, 1995; Edquist, 2005; Malerba, 2002). The systems perspective has proven its virtue for the explanation of innovation dynamics at different levels of aggregation (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2005; Jacobsson & Bergek, 2004). The technological transitions framework has inspired recommendations for policy intervention and broader governance issues by elaborating concepts such as the Multi-Level Perspective (MLP) and strategic niche management (SNM) (Hoogma, Kemp, Schot, & Truffer, 2002a; Kemp et al., 1998; Smith, 2003; Hoogma, Kemp, Schot, & Truffer, 2002b). SNM has proven to be a useful analytical tool to analyse the functioning of a Niche (F. W. Geels, 2002, p.12-15) and can be used to analyse internal niche processes.

In this Chapter, first, the background information on hydrogen will be addressed, then the two major strands of transitions literature will be reviewed, which will be concluded by a proposal from Markard and Truffer (2008) for an integrated framework. In doing so, important concepts such as Niches, Regimes and Landscapes will be clarified. Then the theory on how to analyse implementation of new (renewable) technology, with the use of the system innovation approach SNM is explained.

2.1 Case-Study Background

2.1.1 Energy Transition

It is undisputed among climate scientists that the average temperature on Earth has increased since the mid-20th century (IPCC, 2014). There is also consensus about the cause; this trend is mainly caused by an increase in the concentration of greenhouse gases in the atmosphere, which in turn is the result of strong population growth and expansion in human activities, including use of fossil fuels, deforestation, certain industrial and agricultural activities (IPCC, 2014) [1a]. Since the early 21^{st} century, the majority of the public and politicians have believed that there is a climate problem and that this was primarily caused by human actions (IPCC, 2014). Several measures are possible to minimize damage from climate change, which can be categorized under two main areas: (1) **Mitigation**, where we would emit fewer greenhouse gases by making energy consumption more sustainable and protecting natural areas better, or (2) **Adaptation** of societies by, for example, strengthening dikes and growing better-adapted crops. we – as a society – have chosen to go all-in for the first option (mitigation). The December 2015 Paris Agreement agreed to limit global warming to well below 2°C, but preferably to a maximum of 1.5°C. To reach this goal, the energy sector needs to be fundamentally transformed; This phenomenon is also known as the energy transition. Next to the reduction of greenhouse gases (which is the motive that most determines the pace of the transition), there are other reasons (such as reduced dependence on fossil fuels from countries with dubious regimes and reducing them of unwanted impacts from extraction) for the energy transition, which can be summed up as follows:

1	*Firstly, fossil fuels are harmful to the environment due to, among other things, the CO_2 emitted during combustion. Globally, this was 32 gigatons (4.4 tons per person) in 2015. The global temperature may rise to 1.5 to 2ºC above the pre-industrial level due to further emissions in the coming decades of a total of approximately 500 to 1000 Gt (the carbon budget) (Teske, 2019). Not only during combustion, but also the extraction and refining of oil and the purification of natural gas, carbon dioxide is released, and methane is a strong greenhouse gas.*
2	*Second, oil and gas reserves are slowly depleting. Oil and to a lesser extent also natural gas is imported from countries such as Saudi Arabia and Russia. By reducing (threatening) delivery, they can induce political pressure. This argument weighs especially heavily for many Western European countries since Russia closed the gas tap to Ukraine in early 2006 and 2009 after defaults.*
3	*Third, by burning coal, wood and waste, soot and particulate matter are also emitted. This air pollution causes millions of deaths every year.*

There is essentially no longer any discussion about the necessity of the energy transition (among scientists) (IPCC, 2014). The paris Climate Agreement was a breakthrough (Rijksoverheid, 2015); it called for an unprecedented drop in CO_2 emissions (and other greenhouse gases) to close to zero in 2050. However, the effect differs greatly from country to country, and not all countries recognize the urgency of an energy transition. An analysis of current commitments to reduce emissions between 2020 and 2030 shows that nearly 75% of climate commitments are partially or completely insufficient to contribute to reducing greenhouse gas emissions by 50% by 2030, and some of these commitments are unlikely to be met (Watson, McCarthy, Canziani, Nakicenovic, & Hisas, 2019). In 2017, the world's fuel consumption was 15% renewable (IEA, 2019a), with large differences between countries.

2.1.2 Necessity of renewable molecules in addition to sustainable electrons

The reduction of energy demand, energy use from renewable sources, and electrification are essential ingredients to achieve emission reduction targets. However, in addition to a high degree of electrification, there will also be a permanent and significant need for liquid and gaseous energy carriers in sustainable energy supply. Estimates for the share of this continuing need for molecules vary but will be in the order of 40-60% in 2050 (in 2020 approx. 80%). This is also the case in the Netherlands, where currently, more than 80% of the final energy consumption (industry, raw materials, built environment, mobility, and agriculture) is used by gaseous, liquid, and solid forms of energy: molecules. These mainly come from fossil fuels natural gas, oil, and coal. The other 20% is filled with electricity, of which approximately 85% is also still dependent on natural gas or coal-fired plants. Studies show that the share of electricity in final consumption will approximately double to about 40% by 2050 (IEA, 2019). The share of renewable energy supply is expected to increase by switching from fossil molecules to electricity with heat pumps, electric cars, and some industrial processes. With the increased electrification and the rise in demand for electricity, the supply of renewable electricity will also increase.

Nevertheless, it is currently still not projected to be possible to electrify the remaining 60% of the energy demand. Liquid and gaseous energy carriers remain necessary as fuels for applications where electricity (possibly stored in batteries) is insufficient. Examples include fuel for aviation and shipping, road traffic with heavy, energy-intensive and demanding deployment patterns, and high-temperature heat in various industrial processes. Also, molecules remain necessary in the process industry for the synthesis of chemical products and materials. In the long term, all chemical products and materials that are now produced from fossil hydrocarbons (coal, oil, and natural gas) must be replaced by sustainable variants. Finally, liquid and gaseous energy carriers are needed for large-scale storage and transport of energy, to balance supply and demand of energy everywhere and at all times (Li, Chen, Zhang, Tan, & Ding, 2010; Uhrig, Kadar, & Müller, 2020). This means that there remains an inevitable role for molecules, especially carbon compounds, as raw materials, which must be green, renewable, "climate neutral". Geothermal, biomass, or CO_2-neutral hydrogen can provide this.

Different sustainable molecules will play a role in future sustainable energy supply. Each has its advantages and disadvantages. At present, CO_2-neutral hydrogen certainly also has disadvantages. For example, the cost is still too high, it is only available to a limited extent, and national infrastructure is lacking. Despite these disadvantages, hydrogen is by far the energy source with the most potential in different market segments (Hydrohub, 2019). In international foresight studies, an important role is attributed to hydrogen as an energy carrier. "What makes hydrogen so suitable for its role in sustainable energy supply?" That question is discussed in detail below. It also explains why the molecule of hydrogen helps make our energy supply more sustainable and ensures our energy system's reliability and affordability.

2.1.3 The role of hydrogen in the Energy transition

2.1.3.1 Molecular role: The use of hydrogen in market segments

The great advantage of hydrogen is that there are no CO_2 emissions when burning with oxygen. As can be seen in Figure 2.1, the only by-product of sustainably-produced hydrogen is pure water (through electrolysis or if burned with pure oxygen), since there is no carbon in the hydrogen molecule. If produced in this way, it offers perspectives in making the following four market segments more sustainable, where electrification is not possible or very difficult, pertaining to the Molecular role.

- **Hydrogen as a raw material:** The (petro) chemical industry needs molecules as raw material for its processes. These products are not related to electricity. Hydrogen from oil or gas is often the raw material, but it is relatively easy to replace with sustainable hydrogen.
- **Hydrogen for high temperatures:** Some industrial processes are difficult or impossible to make sustainable through electrification, especially where it requires very high temperatures. This can have various causes. For example, because electrification requires substantial investments, the technology is simply not yet available, or the electrical equipment cannot handle the high temperatures. These high temperatures can be achieved with hydrogen.
- **Hydrogen for (heavy and long-distance) transport:** Various forms of transport, such as heavy freight traffic, commercial shipping, or (large) aircraft, cannot technically be electrified. Hydrogen can also play

a role here, either directly or as a raw material for synthetic fuels. Hydrogen-powered vehicles are zero-emission and quiet. The range and tank speed are comparable to that of traditional fuel vehicles. Hydrogen can be used in buses, forklift trucks, garbage trucks, vessels, and cars (Hydrogen Europe, 2017).

- **Hydrogen for heat supply:** Full electrification of the heat demand in the built environment requires a delicate interplay of reliable insulation, efficiency of the heating systems, and network capacity. The use of molecules limits transport costs, and guarantees sufficient heat supply, simplifying the sustainability of the built environment. We can also think of a combination of electrical and gas systems: the so-called *hybrid systems*. Green gas seems to be the first appropriate molecule for this. In the longer term, hydrogen can be used in combination with an HR boiler or fuel cell.

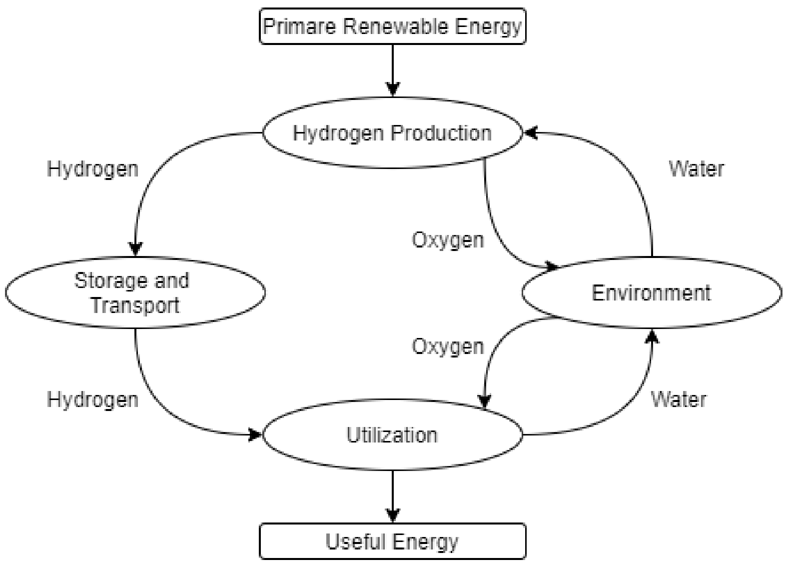

Figure 2.1: Comparison of techniques for energy storage

2.1.3.2 System role: The use of hydrogen for the energy system

In addition to the role that CO_2-neutral hydrogen plays in the sustainability of particular market segments, hydrogen also plays a role when sustainable electricity is not sufficiently available. This relates to the system function: the function that an energy source can perform to ensure the affordability and reliability of the entire energy system. From a socio-economic point of view, hydrogen can fulfill this critical function of the system. Hydrogen enables the connection of the electricity grid and a sustainable gas system. This is also referred to as system integration. Coupling systems have the great advantage that strong elements in one system can incorporate weak elements in another (see Figure 2.2).

CO_2-neutral hydrogen could play an essential role in keeping the energy system reliable and affordable. In summary, this amounts to:

1. **Hydrogen enables large-scale energy storage for the long term**
   The ever-increasing use of green electricity (wind and sun) means that the supply of electricity has a very fluctuating pattern. The temporary storage of electricity is becoming increasingly important to match the supply with demand for electricity. While limited amounts of electricity can be easily stored in batteries in a limited time, it is much more difficult for large amounts of electricity for a long time. For the latter problem, green electricity can be converted to hydrogen ("power to gas"), whereby the hydrogen can be used in various applications (mobility, electricity, chemicals). Hydrogen offers the ability to bridge seasons; It could be stored for the overproduction in the summer (power to gas) and converted back in the winter from gas to power.

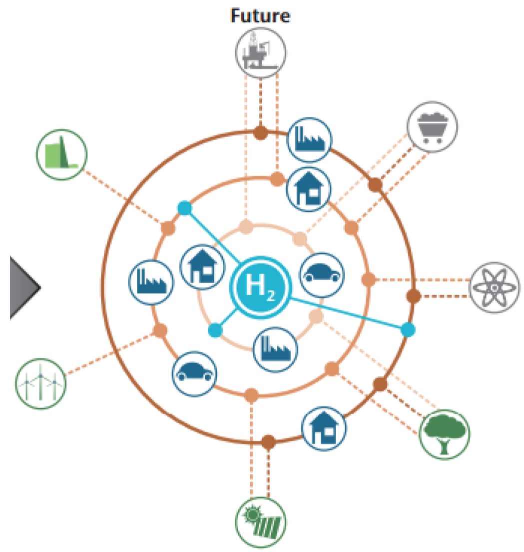

Figure 2.2: System Role of Hydrogen: Hydrogen can link different Energy sectors and Energy T&D networks and thus increase the potential flexibility of future low-carbon energy systems (IEA, 2015)

2. **Hydrogen enables integration of renewable energy :**
   Hydrogen makes it possible to make optimal use of the tremendous potential of solar and wind energy due to its storage capacity, which would otherwise have to be switched off. When needed, the hydrogen in its molecular role can be used in different market segments or converted back into electricity (with conversion losses depending on the type of power plant used).

3. **Hydrogen enables cost-effective transportation and distribution of energy:**
   The Infrastructure Outlook 2050 (Gasunie & TenneT, 2019) shows that the increase in the sustainability of our energy supply will cause the electricity transmission network to run into limits after 2030. The electricity grid will expand considerably in order to meet the growing electricity demand. However, even after this expansion, the electricity grid will not be able to accommodate the (necessarily) growing supply of electricity from solar and wind energy in the longer term. An essential part of the surplus supply must be stored in the form of hydrogen. A hydrogen network is, therefore required to achieve a fully sustainable energy supply.

In Figure 2.3 an illustration can be seen of the four sectors that influence and are mutually influenced by the hydrogen niche and how the molecular role relates to the system role of the molecule.

2.1.4 Hydrogen Economy

Hydrogen is not an energy source like solar or wind energy. It is an energy carrier, a fuel. Hydrogen is the most abundant element on earth, but it hardly exists in its molecular form, H_2: only 0.00005% of the air consists of hydrogen gas (Emsley, 2011; Stwertka, 1996; Boyd, 2014); so, hydrogen gas must be produced. The principle of hydrogen as an energy carrier works as follows: With (electrical) energy, water is split into hydrogen and oxygen (Considine, 2005). This can be done by reforming natural gas, a process that releases CO_2. However, a more environmentally friendly option is to split water into hydrogen and oxygen in a process called electrolysis and using renewable energy (Florida Solar Energy Center, 2007). For example, "green" hydrogen can be made. The energy carrier hydrogen can then be converted back into electrical energy in a fuel cell; this is the reverse process of electrolysis. If green hydrogen is used in the fuel cell, the entire energy chain is CO_2-free. This chain of converting electricity to hydrogen and back to electricity can be seen as a form of energy storage (Page, 2019): when there is an electricity surplus, and electricity prices are low hydrogen is produced; When and where there

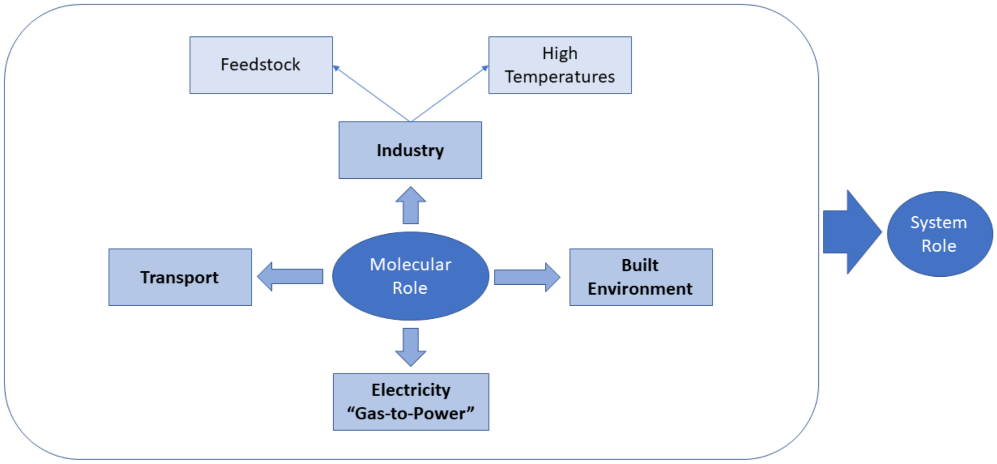

Figure 2.3: An illustration of the four sectors that are influenced by and mutually influence the hydrogen niche

is a need for electrical energy, stored hydrogen is used. As mentioned in Chapter 1, this emission-free chain and the possibility of large-scale energy storage make hydrogen technology attractive in the energy transition: when the influx of renewable energy increases and wind and solar are used on a large scale, and heating is done electrically (in winter), there is a need for large-scale seasonal storage of electricity. This is where Hydrogen technology can play a crucial role.

The introduction of a hydrogen economy is seen as a solution to the problem that the supply of renewable energy sources varies significantly over time (Rifkin, 2002). A hydrogen economy is a concept of an energy economy that mainly or exclusively uses hydrogen as an energy source. So far, no hydrogen economy has been implemented in any country in the world. From a chemical point of view, hydrogen is a primary energy source. However, it is practically not in free form in nature and therefore, must first be obtained using other energy sources (fossil energy, nuclear energy, or renewable energies). This means that a hydrogen economy is not automatically sustainable, but only as sustainable as the primary energy from which the hydrogen is obtained (Armaroli & Balzani, 2006). At present, the production of hydrogen is primarily based on fossil fuels such as the methane contained in natural gas (Liu, Song, & Subramani, 2009; Lee, Elgowainy, & Dai, 2018). Concepts for future hydrogen economies mostly provide for hydrogen generation from renewable energies, which could make such a hydrogen economy emission-free (Deign, 2019).

While a classic hydrogen economy has not yet been sought in any country in the world, there are plans to increasingly integrate hydrogen or fuels such as methane or methanol derived from hydrogen into the existing energy infrastructure. This integration of fuels is part of the energy transition and the expansion of renewable energies (Thomas, 2019; IEA, 2019b). For the successful roll-out of a hydrogen economy, the hydrogen will have to be implemented at all levels of the energy industry (Rifkin, 2002, p.267): (1) Production, (2) Storage and Distribution and (3) Use. In the following sections, all levels of the supply chain of the hydrogen economy will be explained. This understanding is needed for the analysis to be done correctly.

2.1.4.1 Hydrogen Production

The following explains hydrogen production processes, some of which are used on an industrial scale, but some are still in development. A distinction is made between processes that use hydrocarbons and similar compounds and those that use different methods to split hydrogen from water. The production of hydrogen (more precisely, dihydrogen (H_2)) is carried out by various methods that require the separation of hydrogen from other chemical elements, such as carbon (in fossil fuels) and oxygen (in the case of water) (Roman, Santhanam, Miri, Bailey, & Takacs, 2009). Hydrogen is traditionally obtained and extracted from fossil fuels (usually hydrocarbons composed of carbon and hydrogen) through chemical processes (Lauermann, Häussinger, Lohmüller, & Watson, 2013). Hydrogen can also be obtained from water using biological production in bioreactor algae, or by using electricity (by electrolysis - electrolysis of water), or by chemical processes (chemical reduction) or heat (by thermolysis); These methods are less developed compared to the generation of hydrogen from hydrocarbons, but their growth is increasing due to their low CO_2 emissions. They reduce pollution and the greenhouse effect. The discovery and development of cheaper methods of mass production of hydrogen will accelerate the establishment of the hydrogen economy (Rifkin, 2002). The processes are summarized in Figure 2.1.4.1.

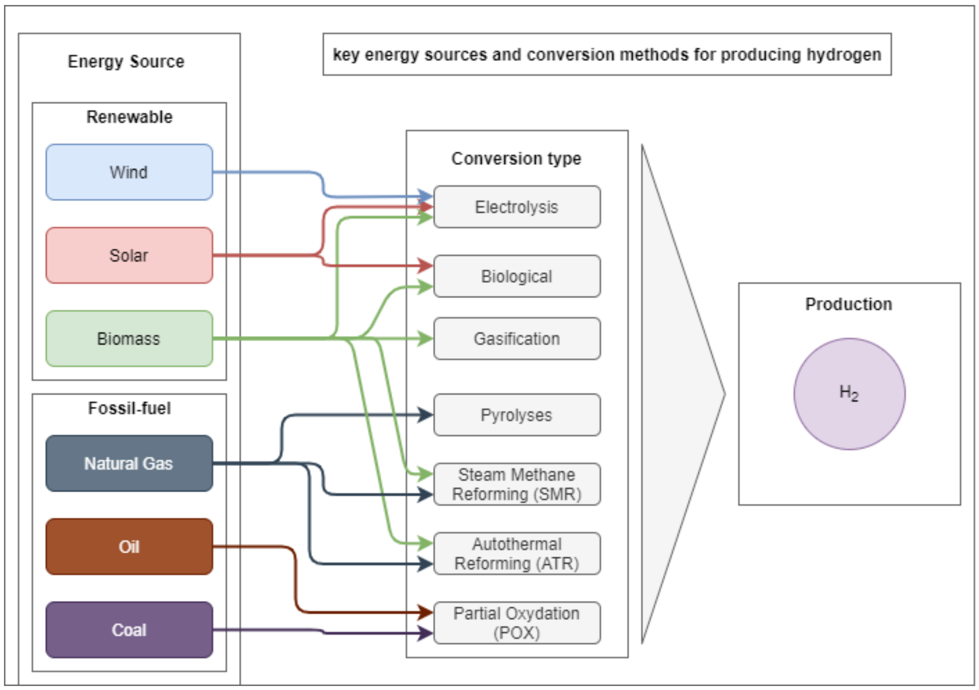

Figure 2.4: Overview of main energy sources and conversion techniques to make hydrogen

Differences in CO_2 emissions are associated with the different production methods of hydrogen. For this reason, there are different terms for hydrogen. If the CO released is not captured, this is called grey hydrogen. If the source is a fossil fuel and the released CO is captured, it becomes blue hydrogen. When hydrogen is converted from a sustainable source (for example, biomass) or sustainably generated electricity, this is referred to as green hydrogen. The palette of hydrogen colors is more extensive, but for simplification, only terms grey, green, and blue hydrogen will be used in this thesis.

- **Grey Hydrogen**
  Virtually all hydrogen currently produced worldwide is called "grey hydrogen." This means that hydrogen has been produced almost exclusively from fossil fuels, primarily from methane done via Steam Methane Reforming (SMR) (US Department of Energy, 2020). Here high-pressure steam (H_2O) reacts with natural gas (CH_4), resulting in dihydrogen (H_2) and the greenhouse gas CO_2. In the Netherlands, approximately 0.8 million tonnes of H_2 is produced in this way, for which four billion cubic meters of natural gas is used, and CO_2 emissions of 12.5 million tonnes are generated.

- **Blue Hydrogen**
  One speaks of "blue hydrogen" or "low carbon hydrogen" when the CO_2 released in the process of grey hydrogen is mostly (80 to 90%) captured and stored. This is also referred to as CCS: Carbon Capture & Storage. That could happen in empty gas fields under the North Sea. At present, blue hydrogen is not widely produced anywhere in the world.

- **Green Hydrogen**
  Green hydrogen, also known as 'renewable hydrogen,' is hydrogen produced with sustainable energy. The best known is electrolysis in which water (H_2O) is split via green electricity into hydrogen (H_2) and oxygen (O_2). In the Netherlands, a large number of parties are experimenting with these electrolyzers on a megawatt-scale. Hydrogen is also released during the high-temperature gasification of biomass.

The amount of hydrogen produced worldwide from natural gas and heavy oil in 1999 was approx. 310 billion m^3 iN. In the Netherlands, approximately 0.8 million tonnes of H_2 is produced in this way, for which four billion cubic meters of natural gas is used, and CO_2 emissions of 12.5 million tonnes are generated. This conflicts with the introduction of an environmentally friendly hydrogen economy, as requested by the European Parliament (European Commission, 2019; European Parliament, 2007). Part of the grey hydrogen also arises as a by-product in the chemical industry, e.g., in gasoline reforming and ethylene production. It also arises as a by-product of Chlor-alkali electrolysis and the production of coke oven gas through coal gasification (Kalamaras & Efstathiou, 2013). The resulting hydrogen is usually used for thermal purposes by burning directly on site.

2.1.4.2 Hydrogen Storage and Distribution

With hydrogen storage is meant the process of storing the gas for subsequent use. To achieve this objective, the optimization of different methods is studied, including high pressures, cryogenic temperatures, but mainly in chemical compounds that have the capacity to store and release hydrogen, either through chemical bonds or by fission absorption. In addition to wanting to be used in the automotive industry, hydrogen has potential use in solar and wind power plants since the excess energy produced during peak generation hours could be stored and used at peak consumption hours.

Hydrogen, compared to hydrocarbons (such as gasoline or propane), is much more challenging to store and transport with current technology. Hydrogen gas has a very low density compared to that of hydrocarbons; therefore, it requires a larger tank to store the same amount of mass. Increasing the pressure would improve the volume by density, making the tanks smaller, but not lighter (pressure tank). Producing compressed hydrogen requires energy to use the compressor, the higher the compression, the more energy is dissipated in this step. Alternatively, hydrogen can be stored in liquid form (as in a space shuttle). However, liquid hydrogen storage requires cryogenics, since hydrogen boils around –252.882 C. Therefore, its liquefaction requires a considerable dissipation of energy because it requires a high energy input to cool it down to that temperature. The tanks must also be well insulated to prevent evaporation. Thermally insulated tanks are often expensive and delicate. Even if the cooling problem is solved, density still poses a challenge. Liquid hydrogen has a lower density by volume than hydrocarbon fuels, with a ratio of about 4 to 1. There is about 64% more hydrogen in a liter of gasoline (116 grams) than in a liter of pure liquid hydrogen (71 grams). The carbon in gasoline also contributes to energy combustion.

Because the volume of a gas is only determined by the number of molecules and not by the size or weight of the molecules, the energy density of hydrogen gas under atmospheric pressure is very low. Solutions are mainly sought in Underground (large scale) hydrogen storage – which is the practice of storing hydrogen gas in underground caves, salt domes, and depleted oil and gas fields - and Formic Acid (Dutch: Mierenzuur) - By adding CO_2 (from the atmo- sphere) to the hydrogen gas, HCOOH (formic acid) is obtained, which is liquid at room temperature and non-flammable.

2.1.4.3 Hydrogen Applications

Hydrogen is an energy carrier that can be used in many different ways. These ways can be grouped into two broad categories:

1. **Hydrogen as a feedstock**
   Hydrogen has been used in this way for decades and is predicted to only increase in the future (Ausfelder & Bazzanella, 2016).

2. **Hydrogen as an energy vector enabling the energy transition**
   In the context, hydrogen has been used on a small scale for a while, and this has seen a stable but small increase in recent years (Hosseini & Wahid, 2016). It is expected that this role will become an essential link in the energy transition in the future and will increase significantly (Hosseini & Wahid, 2016). This is mainly due to the gas's energy density and the many ways it can be used in different sectors (Hosseini & Wahid, 2016).

The next section will discuss these different uses of hydrogen. First, we will go deeper into the traditional uses as a feedstock and then the newer uses as a sustainable energy carrier in different sectors.

Long established uses: Hydrogen as a feedstock
More than 600 billion m^3 of hydrogen (around 30 million tons) is produced annually worldwide for various industry applications and other technologies (iea hydrogen, 2017). A large amount of this is used in the petroleum and chemical industry. In 2019, the most significant application of hydrogen was dedicated to fossil fuel refining and ammonia production. This also makes it essential for the production of fertilizers and methanol, which, in turn, is used in the production of many polymers (IEA, 2019a, p.17). Another application is in refineries, where hydrogen is used to process intermediate oil products (IEA, 2019a). The fractions of use are as follows: 55% of the hydrogen produced is used for the production of ammonia, 25% is used in refineries, and about 10% for methanol production (iea hydrogen, 2017).

The main uses range from (1) Ammonia fertilizer - The most considerable fraction (90%) of the ammonia produced is used for fertilizer production (IEA, 2019a, p.14) – (2) industrial areas – including metalworking, flat glass production, the electronics industry, and applications in power generation, for example, for generator cooling or corrosion protection in power plants – and (3) Fuel production - Hydrogen is used to process crude oil to filter out impurities like sulfur and eventually make refined fuels like gasoline and diesel. In all these processes, the vast majority is grey hydrogen; e.g., (Approx. 75%) of the hydrogen used by oil refineries is grey hydrogen produced from fossil fuels (IEA, 2019a, p.13).

Commencing uses: energy-based uses
As already mentioned, in the energy sector, the fuel cell (FC) is one of the most essential techniques for energy consumption. Fuel cells are electrochemical devices that directly convert chemical energy from a continuous reaction into electrical energy (FCHEA, 2020). Hydrogen use can be split-up into: (1) Hydrogen in Transport – subdivided in direct and indirect use – and (2) use in stationary applications – subdivided into electricity generation and Domestic energy (Built Environment).

1. **Hydrogen in transport**
   Direct use in transport referrers to when hydrogen is used directly by the means of transport without any conversion. This can be done by combustion in an engine or by a fuel cell. Indirect use in transport referrers to when hydrogen is used as a semi-finished product to produce another energy source or convert it into gaseous (Power-to-Gas) or liquid (Power-to-liquid) hydrogen-containing fuels through additional conversion steps. These can, in turn, be used in engines (or fuel cells utilizing a reformer). The applications in transport include, aviation, maritime application, trains, internal transport vehicles (like trucks), buses andpassanger vehicles. Solutions are mainly sought for cars, public transport buses, and trucks (European Commission, 2020a).

2. **Stationary Energy Applications**
   Electricity Generation: Stationary fuel cells can be used for decentralized electricity generation in off-grid areas. This functionality can be used for a growing market for backup power applications (BUP), which is becoming increasingly important worldwide. Fuel cells have higher efficiency (60%) than conventional thermal power plants (Energy efficiency & Renewable energy, 2020; European Environment Agency, 2016). This is advantageous, as it produces relatively little heat as a by-product. The capacity of these backup systems can vary from a few kW to over 1 GWe (Hydrogen Europe, 2017a) [11d]. Additional advantages are (1) a long life-cycle, (2) low maintenance costs, (3) silent, and (4) emission-free electricity generation.
   Domestic Use: If, in addition to producing electricity, heat is also produced, the process is called combined

heat and power (CHP) (Schleup, 2008). If such systems are used in the domestic heating sector, it is also referred to as a micro-CHP or a mini-CHP because this sector involves smaller outputs. The main advantage of fuel cells over thermal heating is the direct electrochemical conversion during electricity and heat generation, which involves higher efficiency. When electricity and heat generation are combined, a fuel cell can achieve an efficiency of Approx. 95% (with an electrical efficiency of Approx. 45%) (ETN & COGEN Europe, 2013). Some other advantages of fuel cell systems are that they are silent, have low maintenance costs, and are locally emission-free.

2.1.4.4 Efficiency of the Energy Chain

When determining the efficiency of a hydrogen economy, the entire conversion chain from the production of hydrogen to the generation of final energy by the consumer must be considered. When hydrogen is used to absorb peaks and troughs in the green power supply, it actually fulfills the role of battery. However, storage in hydrogen is many times cheaper and more efficient than in batteries. KIWA technology previously calculated that the storage of 2000 kWh with batteries costs about 40 thousand euros per year. In contrast, storage of the same amount of energy with hydrogen costs only 400 euros per year. The cause of the large difference in costs can be found in the fact that batteries lose a lot of energy over time. As a result, surpluses from the summer cannot be stored until the summer. KIWA technology has therefore indicated that it sees a future in energy storage in hydrogen. With electrolysis, a percentage of the energy is lost. When electricity is converted to hydrogen and back again, there is a 60% loss. This means that the costs per kw are higher than for natural gas. The efficiency ratings in the sources are sometimes very different because many processes are still under development and their practical production experience is lacking. There is currently no large-scale application, so that above all the efficiency data for hydrogen production have so far mostly been based on the calculation with fossil fuels.

2.1.5 Hydrogen Developments

2.1.5.1 Global Developments

The energy transition has accelerated developments around CO_2-neutral hydrogen. Globally, CO_2-neutral hydrogen is now seen by many as an essential building block for the energy transition. And as an indispensable element in an affordable, sustainable and reliable energy supply. The countries most active concerning green hydrogen are Norway, Australia, Morocco, Chile, Saudi Arabia, China, and Japan (TNO, 2020). The main reason is the vast (potential) availability of cheap, sustainable energy from wind, solar, or hydropower to produce green hydrogen. An exception to this is Japan, which for its energy supply is mainly dependent on imports. The country has developed a strategy to import green hydrogen on a large scale. Simultaneously, they are investing significantly in the progress of the technology itself (ibid.). The Tokyo 2020 Olympics are also known as the "hydrogen games"[1]. The country has been investing heavily in hydrogen for years. The Japanese see the Olympic Games as a perfect stage to show the possibilities of hydrogen to the whole world. In addition to the Olympic games, a new hydrogen city is being built, called Woven City. The construction of this city will start in 2021[2]. According to the Japanese company Toyota, it will be the city of the future, where everything revolves around hydrogen and smart solutions. Finally, the Netherlands is in a good position, partly thanks to their knowledge of gas and electrolysis technology, the significant wind energy potential in the North Sea, and the energy-intensive industry that must actively focus on sustainability.

2.1.5.2 European Developments (Hydrogen Roadmap Europe (FCH-JU))

The European Union also endorses the importance of hydrogen. To this end, the EU launched the Joint Undertaking on Fuel Cells and Hydrogen (JU-FCH). The JU-FCH combines the European industry's efforts, knowledge

[1] The current corona crisis has caused this year's Olympics to be postponed. it will be interesting to analyse whether this postponement will have major impact on the development of hydrogen as well - aside from the direct impact that the crisis has on sustainable development

[2] This will most likely also be affected by the Corona Crisis

centers, and regions in the field of hydrogen applications. The JU-FCH has recently published a new study in which they proclaim the following: "Hydrogen is an essential element in the energy transition and can account for 24% of final energy demand and 5.4m jobs by 2050" (FCH, 2019). This study has been developed with input from "17 leading European industrial actors" and goes about designing a guideline for the large-scale implementation of hydrogen towards 2050. It emphasizes quantifying the socio-economic impact that goes paired with such a transition and exclaims that hydrogen is essential in addressing the climate issue in the future. The report also indicates that "Hydrogen is the only at-scale technology capable of addressing all these challenges" when referring to the necessity of large-scale storage which will be necessary due to the increased electrification and substantial implementation of volatile renewable energy sources into the grid in which seasonal storage and the effective distribution of clean energy at long distances will be pivotal.

2.1.5.3 Dutch Developments (Hydrogen Outlook Netherlands)

In the Netherlands, CO_2-neutral hydrogen is also seen as an essential building block for the energy transition and as an indispensable element for an affordable, sustainable, and reliable energy supply. The draft Climate Agreement contains various measures to bring the 2030 CO_2 reduction targets closer to industry, the electricity sector, and mobility with green hydrogen (Government of the Netherlands, 2019). It includes an ambition of 500 MW electrolysis in 2025 and 3-4 GW in 2030 and points out that hydrogen can fulfill several essential functions in the Dutch energy system. Therefore, the Dutch government has agreed that there would be a programmatic approach for hydrogen that will ultimately focus on the upscaling of electrolysis (ibid.). In 2021 a calculation will be made of how much extra sustainable electricity must be provided to meet the extra demand for electricity through hydrogen and electrification.

Current State of hydrogen in the Netherlands
The Netherlands is the second-largest producer of (grey) hydrogen, after Germany, with an estimated volume of almost 14 billion m^3 per year (176 PJ) (CBS, 2020). The main form of production in the Netherlands is not sustainable and is done using natural gas via a process called Steam Methane Reforming (SMR). A relatively large fraction - approximately 10% - of the Dutch natural gas consumption is used for this purpose (ibid.). Furthermore, hydrogen has been used in the Dutch chemical industry for decades. The vast majority of total production - 14 billion m^3 per year - is used by industry as raw material to produce urea (via ammonia) to make fertilizer. Hydrogen is also used in petroleum refining to desulphurize fuels and reprocess heavy petroleum fractions. Hydrogen is also used in the Netherlands to produce different types of plastics and as a reducing agent and process gas for surface treatment in the glass industry, the metal industry and the semiconductor industry (Government, 2020). Today, hydrogen is increasingly needed to produce biofuels, such as biomethanol.

2.2 Theoretical Background

2.2.1 Clusters

Clusters as a specific target of governments had been made mainstream in particular by Michael Porter (1990). In his paper "The Competitive Advantage of Nations" (1990), his main insight was that the most competitive companies in a country were mainly concentrated in some geographically strategically located places: clusters. One of the most common comments on Porter's cluster theory is that there is no clear difference in framing the clusters (Hermans, 2018). This makes it difficult to define a geographical or administrative boundary so that a subjective cluster framework is often arbitrarily chosen in studies (Martin & Sunley, 2003).

As mentioned in the introduction of Chapter 2, hydrogen clusters stand out from other types of industrial clusters. The concept of a hydrogen cluster indicates that there is a focus on incremental technological innovations, but also the need for radical innovations due to the energy transition. In order to bring the issue of sustainable development more to the forefront, a new perspective on the hydrogen transition and the role of hydrogen clusters is necessary. This perspective can be provided by The Multi-Level Perspective (MLP) and Technological Innovation Systems (TIS).

2.2.2 Multi-Level Perspective

System innovations, like using hydrogen as a primary energy carrier, which are not only a technological departure from status quo, but also impact the social environment, should be approached within a multi-layered systems perspective, called the Multi-Level Perspective (MLP). Generally, the MLP is used as a framework to analyse (socio-technical) transitions, which, as explained in the previous section, are described as large-scale changes in the way social functions are fulfilled. An example of such a societal function is the supply of electricity, which is currently mainly provided by burning fossil fuels. Hence, a transition would need to take place for this societal function to shift to a non-fossil fuel-based supply. The concept of the MLP describes transitions in terms of interferences between three different levels of scale (levels): the macro, meso and micro levels (F. Geels & Kemp, 2000). The different levels of scale are functional in nature and not so much spatial (see Figure 2.5).

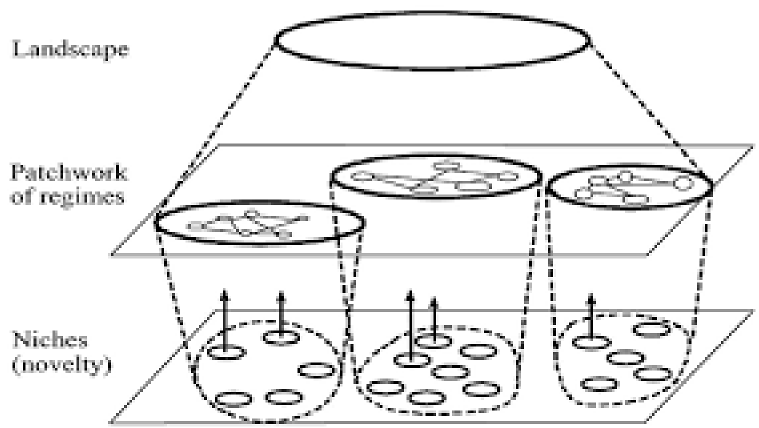

Figure 2.5: (Static) Multi-Level Perspective (F. W. Geels, 2002)

- **Macro-level (Landscape)**: Landscape changes play a role at the macro level, for example in the areas of politics, culture, worldviews, paradigms and macroeconomic aspects. At this scale level, trends and developments form an undercurrent and are relatively slow. Developments at the macro level are external to the regimes and niches, but do influence them (Fischer, 2004, p. 15; Rotmans, 2006, p. 18).
- **Meso-level (Regime)**: Regimes are the established systems here that are intended to perform a certain social function. There is a lot of resistance to innovation at this level, because existing organizations, institutions and networks maintain existing rules, methods and interests (Rotmans, 2006, p. 18). Socio-technical regimes provide an explanation for the embeddedness of certain technical systems, such as fossil-based energy supply, which makes the introduction of (cleaner) alternatives hard.
- **Micro-level (Niche)**: At the micro level, niches develop, often formed by individuals or groups of actors who are open to innovation. At this level there is room for learning processes about innovations, new practices or behavior and the first steps towards a transition are often taken (Fischer, 2004 p. 16). The concept of niches plays a crucial role in transition theory (Rotmans et al., 2000; Rotmans, 2003, 2005; Geels, 2002, 2004, 2005); niches are spaces where deviating practices take place, such as niches for alternative technology (Hydrogen cars), but also in the form of new initiatives and new forms of culture and governance (Rotmans, 2006 p. 18). These deviating practices are made possible by the heterogeneity of the selection environment (prices, preferences, standards, protection of sponsors). Within this micro level is also where radical new technological development including Hydrogen technologies reside and are protected.

Core to MLP is the interdependence between the 3 different levels, all of which contribute to the success of new technology (Rotmans, Kemp, & Asselt, 2001, p.277). According to Rotmans (2006), Dirven, et al. (2002)

and Loorbach (2007) transitions are always the result of developments and events on a large scale (megatrends) and on a small scale (niche developments). Transitions will only be realized if developments at the three different levels link together and reinforce each other in one and the same direction (modulation) (see Figure 2.6).

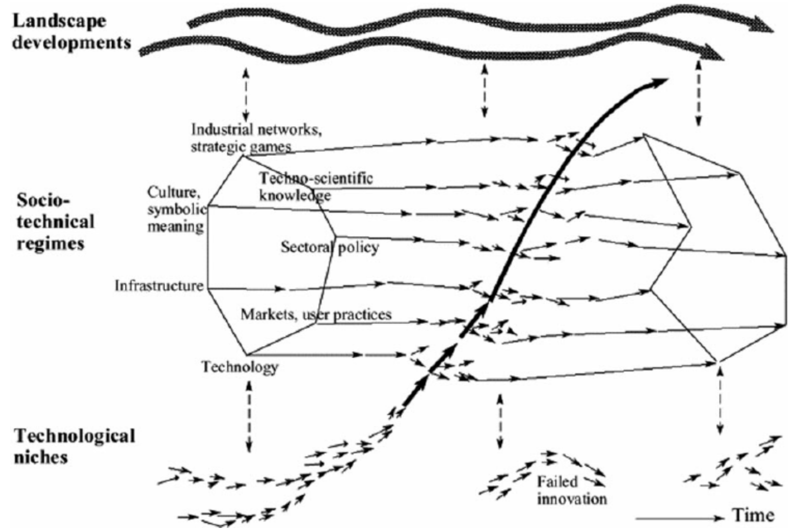

Figure 2.6: Interaction of the different levels for Socio-Technical Transitions (F. Geels & Kemp, 2000)

2.2.3 Innovation system approach

Innovation systems (IS) can be conceptualized as a set of organizations and institutions and the connections between the them (Edquist, 2005). There are numerous relationships between the different components of the IS - between actors, between institutions, but also between actors and institutions. It is possible that institutions cooperate or benefit each other, but they can also be contradictory to each other (Edquist, 2005). Institutions can give actors a boost to carry out certain activities and vice versa to avoid other activities; so, actors are embedded in a so-called institutional context. In the literature, innovations systems that deal with a particular technology or product, are referred to as technological systems (TS). Many studies cite Carlsson and Stankiewicz (1991) who defined a technological system as a: *"network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology* (Carlsson and Stankiewicz 1991, p. 111)." Carlsson and Stankiewicz (1995) describe a TS as an incubation in which innovations are developed, and established technologies are facilitated. According to the literature, the distinction between innovations and established technologies is less critical for incremental innovations, but become crucial if radical innovations are the focus of analysis (Markard & Truffer, 2008).

A theory that is making progress in that area is the sectoral systems of innovation and production (SSI) approach. This is because a distinction is made between new and established products and it is emphasized that ". . . because the notion of sectoral systems includes innovation and production with the related demand and market processes, for analytical purposes, one could examine separately a sectoral innovation system, a sectoral production system, and a sectoral distribution-market system " (Malerba, 2002, p. 251). Both concepts - TS and SSI - contain an innovative part in which products or new technologies are designed, distributed, and used and a production part, in which the advanced products or technologies are further developed. SSI sees technologies or products (i.e., the innovation itself) as an integral part of the system (Hughes, 1987; Malerba, 2002). In contrast, the TS and the IS, as defined by Edquist, do not see it that way. According to Markard and Truffer (2009), this should be seen as an analytical choice. Due to the intricate interaction, they suggest that the innovation itself should be seen as a part of the system that does not fundamentally differ from other elements of the system.

According to the literature, it is imperative and challenging to delineate an IS properly - this means shielding the system and the surrounding environment. (Carlsson, Jacobsson, Holmén, & Rickne, 2002; Edquist, 2005).

First, system delineation depends on the concept chosen (NIS, RIS, SIS, or TIS). Typically, technological systems (TS) cross geographical and also sectoral boundaries (Hekkert, Suurs, Negro, Smits, & Kuhlmann, 2007). Delineation must take into account the structure of technology, such as a knowledge field or a specific market (Carlsson et al., 2002). Even if it is taken so broadly, the system delineation remains challenging in this case, since different technologies or fields of knowledge overlap and influence each other, so there is often a technology continuum instead of single technologies (ibid.). From literature, it can be concluded that there are two types of delineation:

- **Descriptive delineation:** System delineation largely depends on the research question and the reason for the analysis. Also, in this type of system delineation, a further specification in spatial terms is usually included.
- **Conceptual delineation:** System boundaries are defined here so that interactions between the system's elements are more critical than interactions between the system and what happens outside it.

2.2.4 An integrated framework of IS and MLP

Markard and Truffer (2008) propose technological innovation systems (TIS) framework with which the multi-level perspective and the innovation system frameworks can be combined to research developing novelties. Both concepts are mainly developed separately from each other, although they aim to explain similar empirical phenomena and are based on overlapping conceptual foundations. A study by Markard and Truffer (2008) on the fundamentals of technological systems (TS), sectoral systems of innovation (SSI), and niches - mainly looking at the empiric level of aggregation that are typically applied and the relationship they have with innovation and transition processes - showed that the IS and MLP approaches had many overlaps, with points where they can reinforce each other. This led to the conclusion of Markard and Truffer (2008) that a combined framework can offer benefits beyond each concept. In their paper (2008), they make their first proposal for such a combined framework, with the caveat that it would still have to be subjected to empirical test cases. Markard and Truffer (2008) make it clear that this merged framework should apply to a plethora of novelties, looking at innovation dynamics at different aggregation levels. According to the writers, this combined framework would be primarily beneficial if it complements the shortcomings of both frameworks as much as possible.

A TIS is "a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion, and utilization of variants of a new technology and/or a new product" (Markard & Truffer, 2008). The TIS that is the focus of the research is also likely to interact with other TIS, whether it be competition or complementation. According to the authors, contradictory technology may also allow for progress if it destabilizes the regime. If we look at, for example, fuel cells, at the landscape level, factors such as the liberalization of the electricity market or electricity prices for natural gas, can influence the TIS (and the regimes). Several niches are usually considered and developed within a TIS. Besides, a TIS is generally more than the sum of its niches, because it includes multiple institutions that can stabilize the TIS (for example, expressing expectations about the future of Power to Gas) or multiple actors who may not be directly involved in the niche, but still contribute to the TIS. Niches are usually important incubations in which technologies can be tested, and actors come together and learn to cooperate better. Niches can also be (physical) places where actors and technologies from different TIS come together and exchange project details. As niches develop further, the TIS can also grow and mature simultaneously (Markard & Truffer, 2008).

Example: *If the TIS is as defined as proposed by Markard and Truffer, it can overlap and exchange with multiple socio-technical regimes (see Figure C.2). When stationary hydrogen fuel cell technology is considered, it can be determined that there is interaction with centralized electricity generation (Regime1) and decentralized boilers for heating (Regime2). The regimes can form barriers against the development and diffusion of innovation. At the same time, the established regimes are challenged by innovation from the bottom-up, as it potentially offers a solution for (emissive) more advanced products. The amount of resistance also depends on the institutional overlaps or the overlaps in stakeholders of a TIS and the regimes.*

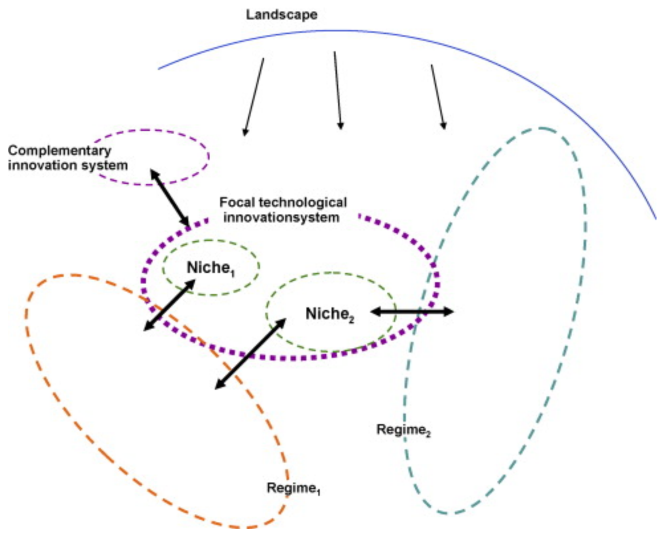

Figure 2.7: Technological innovation system and interactions with the conceptual elements of the multi-level framework (Markard & Truffer, 2008)

2.2.4.1 Conclusion of an integrated framework of IS and MLP

The proposed framework from Markard and Truffer (2008), which combines the strengths of MLP and IS, grants an opportunity to delineate hydrogen clusters. Markard, Stadelmann, and Truffer (2009) have also done this for Biogas in a similar way. The delineation in this way ensures that the whole of the hydrogen innovation system can be taken into consideration and thus ensure that all regimes (industry, electricity (Power-to-Gas), transport, (heat for) built environment) that are of influence are taken into consideration. Markard and Truffer (2008) also state that such a TIS includes different niches, but that it is more than the sum of the niches. This is undoubtedly important to consider when taking hydrogen into account.

After delineation is done in this way, all different types of Niches (for all types of hydrogen applications) that originate within the clusters can be identified and analyzed with Strategic Niche Management (SNM). This micro-level of analysis will be further elaborated upon in Section 2.2.5. After SNM is elaborated upon, the hydrogen clusters in the Netherlands will be delineated in Chapter 4.

2.2.5 Strategic Niche Management

Strategic Niche Management (SNM) is an analytical tool that can be used for a micro-level analysis of niche developments that occur within Hydrogen Clusters. Such an approach is necessary in order to uncover the effectiveness of the innovation system.

Essential to the SNM framework is practical experimentation in so-called (partly) 'protected niches,' where actual users can benefit from experimentation without pressures from the harsh selection processes. In such a case, the development of niche innovations is a result of numerous 'niche internal processes' as well as external developments. From the literature, three of these internal niche processes are of focal importance (Schot, Slob, & Hoogma, 1996; Weber et al., 1999):

- Learning processes;
- (actor) Network building; and
- Articulating visions and expectations.

All three of these have underlying criteria to measure their level of effectiveness in innovation pathways. The "feedback loop," as outlined in Raven (2006) and shown in Figure 2.8 , is an addition to the SNM assessment, which highlights the interconnectedness of the three niche internal processes.

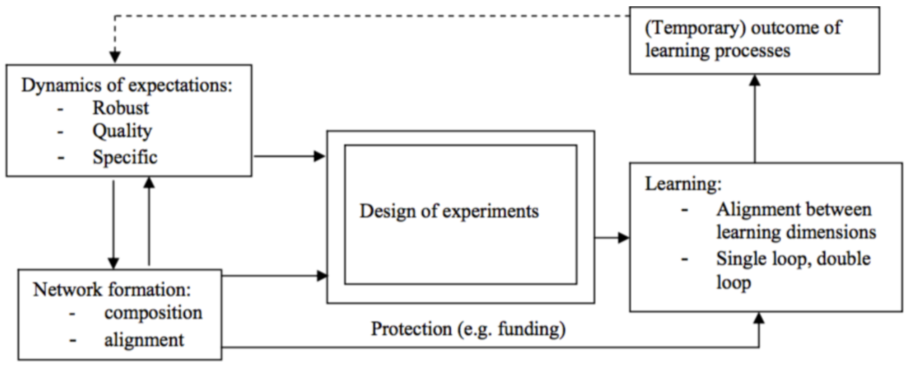

Figure 2.8: Feedback Loop of SNM (Raven, 2005)

Depending on the (voicing of) expectations of actors (providers, knowledge institutions, users, and sponsors), they can choose to become involved with a particular technological solution or experiment. When actors become involved in such an experiment, they experience learning processes on a plethora of different areas, after which they might alter their view and expectations about the product or technology. Based on new expectations, new actors can become involved with experimentation, which can alter the network between actors, potentially leading to new partnerships. These changes in the (voicing of) expectations and the overhaul of the structure of actor-networks can cause the experiment to be revised or even lead to the initiation of entirely new experiments.

External developments in the Landscape, Regime or other Niches (see Figure 2.6), have a significant impact on the niche internal processes that take place in the immediate environment of the experiment (see Figure 2.6). Research by Raven (2005) points out that shifts in visions and expectations can largely be explained by external factors.

2.2.5.1 Specified internal Niche Processes

According to van der Laak (2007), expectations are considered to be effective if they are (a) supported by multiple actors (Robust); (b) specific and clear (Focus); and (c) backed by sufficient evidence through e.g., experimental learning (High Quality) (Laak, Raven, & Verbong, 2007).

The same goes for 'building of social networks': "Well-functioning networks are anticipated to generate co-ordination and convergence between varying expectations" (Mourik, Daffertshofer, & Beek, 2006). According to van der Laak (2007), Social networks can be considered "Highly-Functioning" when a comprehensive variety of actor types engage and alignment among actors increases.

Within the Learning process, two types of learning can be distinguished: 'First-order' learning and 'Second-order learning.' First-order learning includes learning and optimizing processes based on the collection of data on numerous factors e.g., on the technical infrastructure, advancements within the industry, impact on the environment, and user experience. (Hoogma et al., 2002a). Second-order learning occurs when the learning process questions the fundamental hypotheses regarding the technology e.g., social values and standards concerning the technology. Principal in second-order learning is the adaptability to reevaluate expectations and reconstruct the social network (Mourik et al., 2006). The learning process can only be considered as being "sufficient" if it includes both first-order and second-order learning (Schot & Geels, 2008).

SNM is a very useful analytical tool, yet it is widely criticized for its broadness when measuring the three internal niche processes. The criteria mentioned above are interpretable by the researcher and can be influenced by personal bias. In the final section of this chapter (Section 3.4), this will be addressed further, with the choice of theoretical frameworks and additions to SNM itself. SNM is also criticized for focusing on 'planned, well-ordered, and consensual management processes (Farla et al., 2012). Raven et al. (2011) address this by making a distinction between local and global events, which makes it possible to take into account 'unplanned events.' This is is also elaborated upon in Chapter **??**, with a methodological approach that, for the most part, counteracts this point of criticism.

Recent studies have attempted to further contribute to specifying the criteria. For example, Turnheim and Geels (2019), confront the common understanding in the SNM framework with an in-depth longitudinal case study of modern French tramways (1971–2016), which represents a particular technology class: *local infrastructure systems*.

Turnheim and Geels' (2019) case confirms the relevance of existing SNM-concepts, but also points to three pattern deviations (Ibid.):

1. Incumbent actors from adjacent regimes can have a principal role in the advancement of radical alternatives;
2. The timing of the voicing of expectations can have a significant influence on the transition pathway, e.g., "the early formulation of highly specific visions can effectively guide search paths (as opposed to a usual prescription about more open-ended approaches to foster innovative variety creation)" (Turnheim & Geels, 2019);
3. Particularly important projects (which the authors call 'landmark projects') can have a stimulating effect on the advancement of innovation. They propose that it can be a productive way forward for sustainability transitions research to investigate a more extensive diversity of diffusion and transition patterns, which are more based on the timing of actions and the different roles of actors.

These new insights will be considered in the final choice of a theoretical framework and the methodological approach that will be used further for the research of this thesis.

2.2.5.2 SNM analysis of whole supply-chain

For hydrogen, *production - distribution - use*, are so strongly complementary to each other that one activity cannot be expected to get off the ground without the simultaneous development of another. More specifically, the production of green hydrogen (building large-scale electrolysis plants) is capital-intensive. For this investment to be profitable, hydrogen should be used for all of the industries that it can be used.

From an SNM perspective, it means that simultaneous initiation of experiments at each of the three stages in the chain would, therefore, seem to be vital for the emergence of a viable Hydrogen-based production chain as a whole (together they are more than the sum of their parts). Thus, effective experimentation needs to exhibit networking, expectations/experimentation, and learning within and across the different production stages. It is pivotal that all three aspects of the supply-chain simultaneously show good niche performance. A similar approach to analysis has been used by Eijck and Romijn (2008) for the analysis of Jatropha in Tanzania.

2.2.5.3 Conclusion of the Theoretical Approach: Hydrogen Cluster Delineation

After the methodological approach is explained in chapter 3, a final section 3.4 summarizes the way in which the previously described theoretical concepts will be used in the continuation if this thesis. Simultaneously this can be seen as an analysis manual that will be used to answer the research question:

RQ	*"How has the hydrogen niche been developing in the Netherlands, and how can this be facilitated?"*

Chapter 3

Methodology

The methodology used to carry out the suggested research is outlined in this chapter. In the first section, the research objective is discussed in detail. This is followed by an explanation and expansion of the research questions (RQs). The last two sections explain the research design and methods used to collect and analyze the data.

3.1 Research Objective

As touched upon in the introduction, the overarching objective of this thesis is to add to the body of research about the socio-technical implementation of hydrogen to contribute to the energy transition. Although the technical feasibility of hydrogen has received extensive attention from the academic research community, which has covered issues such as storage in salt mines; infrastructural feasibility (Gasunie & TenneT, 2019); techno-economic feasibility of hydrogen. None of them have performed comprehensive research specifically on managing the implementation of hydrogen technology from a socio-technical perspective to identify structural and societal changes that need to be made for wide-spread adoption to take place.

Since wicked issues do not have one approach that can be implemented on a broad scale, this research will be done by explicitly looking at the way that the Netherlands has dealt with the implementation of hydrogen, what its barriers are and how these can be overcome. Recently, hydrogen has received much attention from scientists and governments and is regarded to have great potential. However, there is currently still a lack of practical application, and hydrogen is still a niche technology across the world and in the Netherlands. Due to Netherlands' huge hydrogen potential, due to the gas infrastructure and the exceeding necessity to close the 'Gaskraan' (natural gas production), this research will focus on the current implementation and future goals to see what has been done and how it could be done better.

Research has shown that the extent to which user expectation is satisfied is one of the critical factors of the success of hydrogen (Rai & Andrews, 2012). As the social impact of hydrogen becomes increasingly present in the socio-technical landscape, studying the transition from a Niche technology becomes increasingly relevant as the technology is gaining worldwide popularity.

This thesis aims to discover the current trajectory of the Netherlands' transition. As mentioned in the theoretical framework, transitions are significant changes in the way society functions are fulfilled through socio-technical systems. Since the implementation of hydrogen has not been optimal, it will be useful to study how the technical transition has been handled to determine which aspects of the transition are lacking. This is important since technological transitions not only involve technological changes but also changes in user practices, regulation, industrial networks, infrastructure, and symbolic significance or culture.

Furthermore, this thesis aims to contribute to the existing body of empirical energy transitions research in developed countries, while contributing to a certain extent on energy transitions in general. In order to effectively address these points in this research, a Research Question (RQ) has been formulated, expanded to a set of Supporting Questions (SQs), which have been laid forth in Chapter 1.

3.2 Methods

The proposed thesis aims to analyze the implementation of Hydrogen in the Netherlands and how the country can improve its innovation system to further promote an upscaling of Hydrogen. To research this, mainly a micro-level of analysis will be used. As part of the micro-level analysis, a qualitative case study approach will be taken. This will be done through the process perspective. In the following section, the process perspective will be explained, and a case is made as to why this is useful the research of hydrogen clusters with the Strategic Niche Management.

3.2.1 Case Study

To investigate the development of Hydrogen in The Netherlands, a case study will be performed on two hydrogen clusters in The Netherlands, namely the port of Rotterdam and Eemshaven. The most noticeable results from the extensive existing literature will be collected to identify all significant socio-technical energy-related SNM experiments with hydrogen in the three clusters. Therefore, it is appropriate to adopt a qualitative approach, as Bauer and Gaskell (2015, p. 7) state that qualitative research is intended for "exploring the range of opinions, the different representations of the issue." In this case, all relevant news articles, reports, and websites (primary data) will be collected to obtain all relevant data related to the three internal niche processes or broader landscape and regime developments. These 'relevant events' will first be determined from the literature, and through the research approach itself, criteria can be added. The observations of the events will be verified through interviews (secondary data).

Case studies are often found to be one of the most applicable research methods in answering exploratory 'how' questions - as is the case with the Research Question of this thesis (Yin, 2009). Since it is intended to "cover contextual conditions and not just the phenomenon of study" (Yin, 1993, p. xi), a case study is fitting. In this thesis, the phenomenon of study is socio-technical transitions. The context in which this phenomenon is applied is that of the pursuit of hydrogen in the Netherlands. However, qualitative research is limited by the fact that it is often the victim of the question: "How do I know that you know (what you are claiming)?" (Gioia et al., 2012), which can lead to scientific skepticism. Additionally, in performing case studies, the generalizability of the study is often questioned (Jensen & Rodgers, 2001).

As this thesis does not aim to generalize for countries all over the world in how they implement hydrogen, but rather an in-depth understanding of the Netherlands, the case study method seems to be applicable.

3.2.1.1 Case Selection

As discussed in Chapter 1, this research will focus on the Hydrogen Cluster formation in the Netherlands. This research will focus on the two major Dutch clusters, namely the Port of Rotterdam Cluster and the Eemshaven (Groningen) Cluster. From a quick scan, these two clusters have the most activity (see Figure 3.1). They are the most progressive when it comes to hydrogen development, based on the number of collaborations, news articles, vision formation from the quick scan. The benefit of looking at two different clusters is the comparison that will be possible, including lessons that can be learned from one cluster that can be beneficial for the other.

Additionally, the methodology that will be used (Event Sequence Analysis) is especially well-suited for comparison across different cases. This is especially interesting when taking into account these specific two clusters, which have experienced such different developments on such different time scales (Eemshaven started earlier, yet Rotterdam has recently made more progress). When taking into account the theoretical framework of MLP and SNM, it will be interesting to compare these two clusters, since they seem to have such different expectations for hydrogen and seem to focus on different aspects of the molecule (different production types for different end-uses).

Figure 3.1: Topographic image of the Netherlands with depiction of the location of industry clusters. Red: North-Netherlands (Eemshaven/Delfzijl) Cluster; Yellow: Amsterdam (Noordzeekanaal) Cluster; Blue: South-Holland Cluster (Rotterdam/Moerdijk) Cluster; Purple: Zeeland Cluster; Green: Limburg (Chemelot) Cluster.

Sampling in case studies is mostly strategic and purposive, taking into account the unique context of a case (Miles, Huberman, & Saldana, 2014). As this thesis is focused on the case in the Netherlands, a strategic and purposive sampling method is applicable. The benefits of this purposive sampling should be noted, since it allows the selection of a case containing a feature or process of interest, according to (Silverman, 2010). This case is applicable as it is part of the Netherlands, yet has its unique characteristics, just like every cluster in the Netherlands.

The cluster analysis will be done with Event Sequence Analysis (ESA), which looks at reality from a process perspective (explained in the following Section). The theoretical approach to the analysis of the performance of the Dutch clusters will stem from transitions theory. The analysis would build on the theoretical concept of Strategic Niche Management (SNM), which indicates how niches should be managed within its socio-technical context to become mature and potentially take over market share within the established regime.

3.2.2 Process Perspective

The main characteristic of the process perspective is that reality is seen as a consequent flow of events. It is not necessarily a given that 'stable entities' (such as firms) exist. However, according to this perspective, they are "emerge from the soup of events as lineages, as events that keep happening the same way" (Abbott 2001, p.296). It follows that we should study phenomena of interest as a sequence of events. This places the focus of the research on reconstructing such a 'sequence of events' to find out whether there are typical patterns in the emergence of the events.
Based on the literature review, it has been found that the multivariate perspective is now mainly used in the social sciences. According to Abbot (1988), there are three critical differences between the multivariate perspective and the process perspective:

- Firstly, in the process perspective, entities can change over time or even disappear altogether without methodological problems.
- Secondly, in the process perspective, it is also imperative when a particular event takes place since even relatively small events can have a significant impact depending on its position in the sequence.
- Thirdly, the process perspective places great importance on the sequence of events, while the sequence effects are not considered multivariate.

The process perspective is unique in that it deals with questions about the timing and place of events within the broader chronology of events. Research in the context of the process perspective can be formulated in three ways:

1. **Backward approach:** Here, the researcher starts with a specific outcome situation and investigates which events led to this (Mayntz, 2004). This approach requires research questions that seek to understand a process from which a particular event or stable entity originated.
2. **Forward approach:** Here, the researcher chooses a starting point, and the events that follow are inventoried and investigated. (Van de Ven et al. 2000). A local authority plan to develop a hydrogen cluster or specifications of hydrogen/climate goals may provide a starting point. This approach can also look at the different outcome pathways that could follow from a specific starting point.
3. **Counterfactual approach:** Here, the researcher wants to understand the specific role of events by asking questions such as, "What if this (set of) event (s) had not occurred?" (Hawthorn, 1991). This approach takes specific events that are considered particularly crucial under the microscope and tries to find out how important they have been in bringing about certain consequences.

Boons et al. (2014) argue that there are three categories of theoretical building blocks that need to be employed while emphasizing that this is not an exhaustive listing. Furthermore, these are all building blocks that have to be elaborated upon with literature from innovation and transitions studies, more specifically, Strategic Niche Management:

1. **Conceptualizations of outcomes:** This refers to the network of connections between the various incidents. In addition to cluster-level outcomes, they can also be studied at higher aggregation levels (societies), in terms of diffusion of niches across the country (Boons et al. 2011).
2. **Types of process:** The second building block is about the general statements about the flow of events that flow from a defined starting point or that seem to lead to a particular conclusion. Theories are needed to determine in advance which events will be considered that are of great importance to the process. The SNM literature attaches great importance to experiments that influence the three internal niche processes (Building of social networks, the voicing of expectations, and learning process (Geels, 2002)), which, in turn, impact the transition. Within these niche processes, it is essential to consider all relevant variables. To add to this, MLP literature can be used to specify the process through which the Niche spreads through society. Using these mechanisms as the basis for a process analysis may provide insight into the dynamics of niche diffusion into the established regime.
3. **Types of linkages between events:** In addition to a theoretical framework with which relevant events can be identified, theory is also needed to determine how events are linked in so-called "sequences" (Abbott, 1984). Van de Ven and Poole (1995) make a useful distinction between teleological, life cycle, evolutionary, and dialectical processes.

3.2.3 Event Sequence Analysis

Over the past decades, various researchers have developed methods that use tools to carry out the process perspective research (Abbott, 1988, 1990, 2001; Abell, 1984, 1987; Poole et al., 2000). A recent development of this is the Event Sequence Analysis (ESA). ESA provides a set of methods and techniques to systematically address longitudinal research (Spekkink and Boons, 2011; Boons and Spekkink, 2012b), where processes are considered fundamental, while the outcome of the process is ontologically secondary (Rescher, 1996). Up to a point, ESA is comparable to a case-study method, in which a systematic case narrative is developed (Yin, 2009). However, ESA goes a step further in providing tools to systematically identify and compare the specific chronological outcome of events (Spekkink, 2013). Such comparisons can be performed within a case, but also across different cases. The following sections discuss the different steps to be taken for the ESA analysis.

3.2.3.1 Steps for ESA analysis

Figure 3.2 shows a diagram that depicts the process that the researcher will take to conduct the ESA analysis successfully. In the subsequent subsections, the different steps will be elaborated upon.

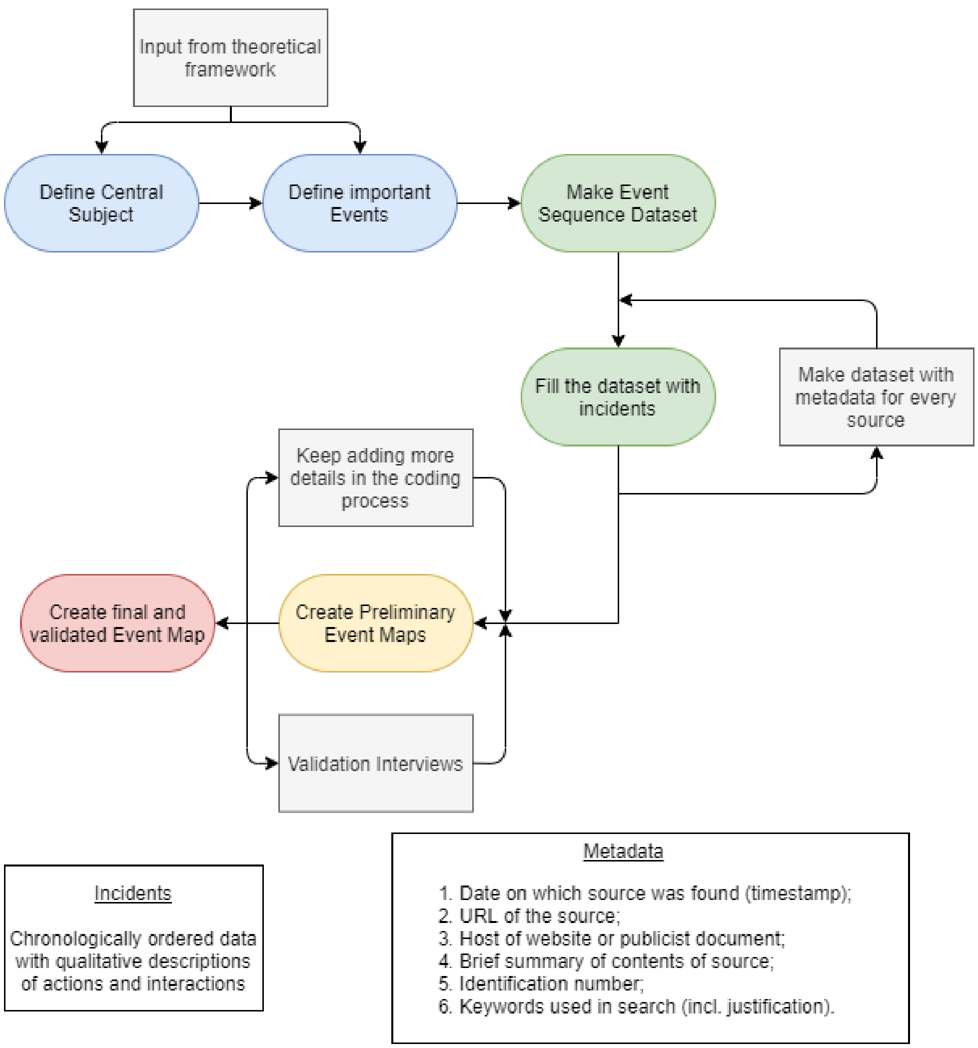

Figure 3.2: Diagram that indicates the steps for Event Sequence Analysis (ESA), what the iterative steps are and how the final event map will eventually be created (Forward Approach).

3.2.3.2 Central Subject

In ESA, a process is viewed as a chronological consequence of events that describe how entities are created, developed, and possibly disappear over time. An essential step in considering a process is defining a central subject, as well as defining the different types of events that this central subject goes through and brings about (Poole et al., 2000). “The central subject can be any kind of entity, such as an individual actor, a group of actors, a lineage, a social movement, a machine, or a RIS” (Spekkink, 2013). Due to the process perspective, it is vital to keep in mind that the central subject is not a fixed entity but evolves as events occur. These developments are fundamental in ESA, as the explanatory power is in charting how interesting phenomena change over time.

3.2.3.3 Events

Events can be seen as the theoretically significant events that the central subject goes through or brings about. The relevant type of events should be identified based on the theoretical or conceptual framework of the researcher. These frameworks must also specify the mechanisms that link the different types of events (Abbott, 1990). Preliminary research shows that, although it is essential to identify a set of relevant event types in advance, additional event types may be identified at a later stage of the research process (Vayda, 1983). When this happens, the researcher should always consider the theoretical implications of adding new types to avoid conceptual inconsistencies.

3.2.3.4 Data collection

After defining a central subject and relevant event types, longitudinal data can be collected for the process that the researcher is interested in (Spekkink, 2013). When collecting data, the frameworks of the central subject and the type of events will serve as guidelines in identifying the relevant data points for the research. The collected data will be included as incidents in a chronologically ordered event sequence dataset. Incidents are short, empirical descriptions of events within the process. In ESA, these descriptions are used as indicators for the emergence of events (Spekkink, 2013). The following should at least be taken into account when describing an incident:

- The date on which it occurred;
- The actors or objects involved;
- The (inter) action taken by the actors or objects;
- The source of the information (based on Poole et al., 2000).

Different types of data sources can be used in this type of research (Spekkink, 2013). Boons et al. (2014) report that they have a positive experience with the use of news archives, documents, reports, and web pages as primary data sources. A log can be used to keep the data collection manageable and reliable. This data can be validated by testing the resulting case descriptions based on the experiences of actors involved in the process. Retrospective interviews or workshops with multiple actors may be used here (Boons, Spekkink, & Jiao, 2014; Spekkink, 2013). Both techniques have their pros and cons.

3.2.3.5 Coding

After inventorying raw data in the event sequence dataset in the form of incidents, they must be coded separately as indicators for different types of theoretically conceived events. The researcher’s coding scheme must be based on the theoretical framework, which, in the case of this thesis, will be based on SNM and MLP. Examples of codes that come from the theoretical framework are: the articulation of expectations, desires, and opportunities, network building such as orientation, planning, feasibility study, and learning processes after implementation and contextual influences (MLP).

3.2.3.6 Colligation

After a reliable coding scheme has been developed, and all incidents have been coded, these incidents must be colligated into events (Abbott, 1984, 1990). In this process (colligation), the investigator must merge the incidents that make up an event. The process of colligation also ensures that the duration of events can be mapped. Although incidents only show a specific action or interaction, events can represent a broader range of actions that represent different facets of the event (see Figure 3.3).

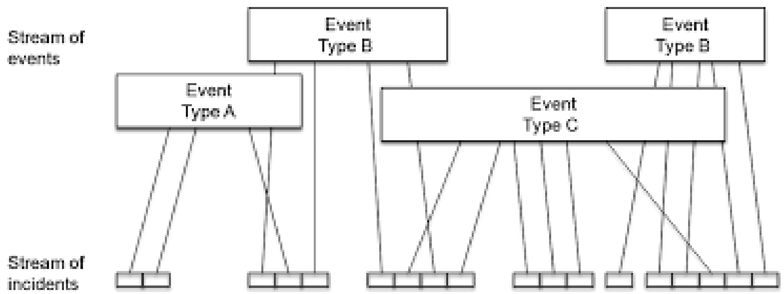

Figure 3.3: Relationship between incidents and events (Boons et al., 2014)

3.2.3.7 Data Analysis

One or more sequences of events emerge from the process of coding and colligation. These can be analyzed in various ways for noteworthy developments over time. According to Spekkink (2014), all types of analysis techniques have a common characteristic, so that they are all looking for "recurring patterns in sequences of events." The most relevant for this thesis research is visual mapping, which displays sequences of events on a time scale in a so-called event map. In such a visualization, it becomes visible which events influence each other. It can give insights into the effectiveness of experiments, the influence of landscape shifts, and ultimately showcase the functioning of the niche processes.

In such a visualization, a visual difference can be showcased between different clusters of event types. For this thesis, a differentiation in color will be made for:

- Events that occur within the three different levels of the MLP (Landscape, Regime or Niche);
- Events that are specified for the three different internal niche processes of SNM (voicing of expectations, building of social networks, learning process);
- Events that have direct or indirect impact.

By mapping two different clusters in this way, a direct comparison can be made of the difference in the development of the two clusters. This is crucial for hydrogen due to the different types of production, distribution, and use. Such a visualization could show the different approaches that different clusters take in hydrogen developments and experiments. E.g., one cluster may focus on becoming an electrolysis hub, while another focuses on rolling out hydrogen on a large scale, regardless of the production type (probably leading them to use a majority of grey or blue hydrogen). Additionally, this visual representation can show the different time-frames in which different clusters develop and the speeds at which they develop, depending on the number of events in a given period.

3.2.3.8 Outcome Assessment

When it comes to the process perspective, the researcher should clearly make a differentiation between 'point outcomes' and 'outcome trends.' "Outcome trends allow the researcher to connect impact with events of SNM

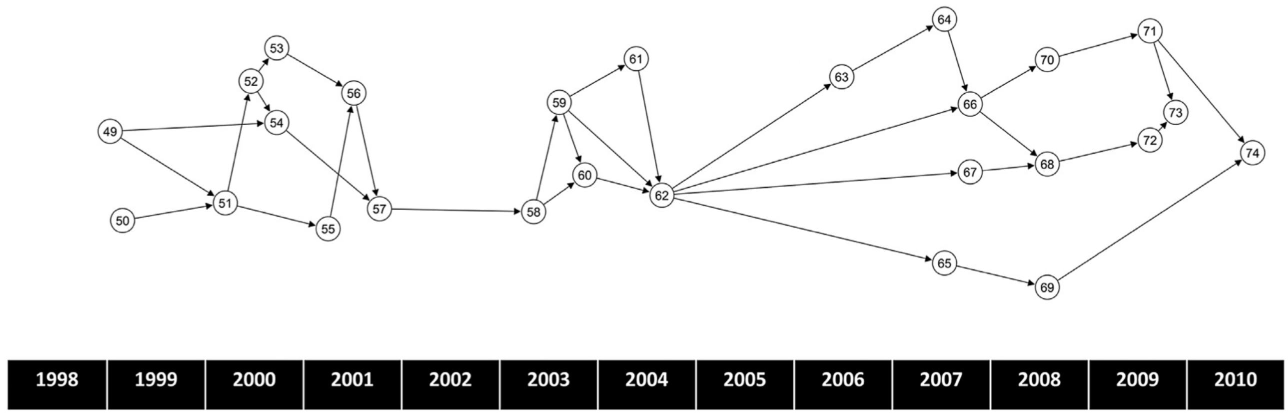

Figure 3.4: Example of an Event Map that shows linkages between events. The numbers correspond to incidents in chronological order (Spekkink, 2017)

and MLP. This provides insight into the role of certain event sequences in producing changes in impact (Boons et al., 2014)."

Several tools can be used to evaluate this outcome in a structured way. An example of this is the study of the outcome in terms of connections between autonomous economic entities through Social Network Analysis (SNA). Form the literature study; this appears to be an effective way to study structural characteristics of social network building between actors (Ashton 2008; Paquin and Howard-Grenville 2012; Domenech and Davies 2011; Powell and White 2005; Staber 1998).

3.2.3.9 ESA for hydrogen clusters in NL

The analysis of this thesis will build on the theoretical concept of SNM, which indicates how niches should be managed within its socio-technical context to become mature and potentially take over market share within the established regime. The Process will be approached from the **Forward approach** in which a significant starting point will be identified (Kyoto Protocol, Paris Climate Agreement, or a local climate initiative). For the analysis, it seems interesting to take the Paris Climate Agreement in 2015 as a starting point, seeing as there was a period of stagnation before this point in which initiatives were negligible. After 2015 hydrogen has made considerable developments. Nevertheless, through the process of data collection, it will become clearer whether there have been significant 'events' before 2015, which also needs to be included in the analysis.

3.2.4 Data Collection and Processing

The ESA is very data-intensive, as it requires the collection, processing and analyzing of longitudinal data that spanned over a long period of time (Spekkink, 2013). Furthermore, Boons, et al., (2014, p. 347) indicate a similar opinion: "data must cover a substantial time period, and data sources may not be available for all theoretically relevant events." The data gathered for this hydrogen case study was based on news items, documents and web pages. Even though the information was presented differently in each of the three types of sources, there was enough overlap for triangulation of data. The documents and web pages were collected on the basis of a protocol that developed before initiation. The data that was found, was originated by a plethora of different stakeholders in the relevant hydrogen niche-related events (between 2000 and 2020) from all different levels of society.. For the collection of documents and webpages an Internet search was performed, using the Google search engine, specifically utilizing different (hydrogen) news-related websites, including 'Energeia', 'WaterstofNet' and 'AllesOverWaterstof'. An electronic logbook was developed to make the data collection process efficient, by tracking how the searches were carried out, by noting down the used search engine, websites and the keywords. After finalizing the conceptual model and defining the central subject under study, the relevant event types could be identified, after which the data collection process started, which took approximately 3.5 months of intensive work (from March 1st to May 10^{th}).

In the process over 125 web pages, 75 documents and 350 news items were collected (some were duplicates or very similar because of overlap in search results. These data sources led to a final dataset consisting of 151 chronologically ordered events, which were substantiated with multiple web pages, documents and news items, which were all read and analyzed individually. This was the result of multiple rounds of data collection, where overlap between news articles was sifted out. In addition, some sources appeared to be irrelevant to the research and were not included in the final dataset (after three rounds). In a first round of data collection, an Excel-file was created as a database with all the incidents that were found, ordered per sector (in different sheets). There were then analyzed and filtered in a second round to create the event sequence dataset using a software created by Dr. Spekkink, dedicated to ESA analysis; throughout the data collection process incident descriptions were entered into the dataset that was derived from the raw data. The specific coding software allowed for the coding of incidents in a systematic way, with required information, including the source, date of the incident, incident description, additional details about the origin of the source and some extra background (see Fig. 3). This stored the incident including sources within the software with an identification number, which was distinct per incident and was used as identification. This allowed structured navigation through the collected data and use of identification numbers in the event sequence dataset as references to the sources of the incident descriptions.

3.2.4.1 The coding schema and data analysis

After all the incidents were entered into the event sequence dataset and some necessary corrections were made, a coding scheme and coding procedure was developed based on the conceptual framework (SNM and MLP). The codes for different types of event suggested by the (theoretical) framework were developed, firstly for events that belong to the three different levels of the MLP (Niche, Regime and Landscape) and secondly for events that are associated with the three internal niche processes (expectations, learning, network). Further differentiation was made for the different sectors (mobility, industry and energy), with extra differentiation within each sector (e.g., buses, cars), and the location where the event took place (Global, European and Dutch), which could be used by the software in order to differentiate (color-wise) in event types when assessing the event maps.

The codes were also subject to addition after a first round, to capture some types of events that were not arbitrarily categorizable under the previously determined codes. These additions were never departures from the logic of the conceptual framework, rather they elaborated the framework; the most notable example was the establishment of the organization of influential seminars, attempts by actors to influence their physical or political context and last but not least the regional differentiation of events and their proclivity to form within (industrial) clusters, with an emphasis on the Northern Netherlands and South Holland clusters. Visual mapping was used for analysis (discussed by Langley (1999)), to give a visual overview of the sequences of events that were analyzed in this thesis and to visualize the interrelationships between the sequences of events. This visualization was achieved through the specific software, where linkages were manually placed between chronologically following inter-sector events and direct inter- and intra-sector events which do not necessarily follow chronologically, but have an explicit and obvious influence on each other. Thus, for this part of the analysis, chronological linkages were mainly determined per sector and linkages between inter-sector and intra-sector events were placed when these were explicitly mentioned or obviously inferred from the incidents that make up the event (from news items, documents or web pages).

3.2.4.2 Validation interviews

After the final round of coding, a total of three interviews were performed with industry experts on the hydrogen transition, each with an expertise in the three different sectors that are determined in Chapter 4 (energy, industry and mobility). Two of the interviewees were Accenture consultants with an expertise in the hydrogen transition, one with an explicit focus on the mobility sector and the other with a focus on the energy sector (Built-environment and Electricity). The final interviewee was from the TKI Gas, with an explicit focus on the industry sector. These interviews had two purposes; they were mainly used to check whether my reconstruction of the process corresponds with their experiences. Furthermore, due to the qualitative nature of the theoretical approach, the interviews were also used as a way to increase the body of data and validate the theoretical findings of subjective experiences of stakeholders. The results of the interviews only validated or added to the body of data and thus gave no reason for revision of the ESA. Finally, the findings of the internal niche processes were also in line with what was found in the coding process, with some additional information coming from the interviews.

3.3 Research Design

Figure 3.5 illustrates the steps that will be followed to answer the Research Questions. The numbers in circles represent the SQs that will be answered in each step. When the final step is finished, the RQ will have been answered.

As shown in Figure 3.5 first theories on Transitions and innovations, in addition to specific knowledge on Hydrogen Clusters, which have been explored in Chapter 2 will directly provide input for the coding scheme.

- The framework that integrates TIS and MLP proposed by Markard and Truffer (2008) will be used for definition of the central subject.
- The specific criteria for the study of Cluster performance, which results from exploration of SNM (3 niche processes for the whole supply chain) as well as MLP (Landscape and Regime Shifts) and specific hydrogen cluster theory will directly serve as input for the definition of relevant events and incidents.

Once the coding scheme is done, the Event Sequence Analysis will commence. This entails the exploration of web sites, news articles, documents and meeting notes that contain relevant events for all the relevant central subjects (Port of Rotterdam and Eemshaven). After the raw data is gathered and coded properly, the data needs to be colligated. The colligated data will then serve as direct input to create the first event graphs, which will provide a first illustration of the development of the hydrogen clusters.

Since the coded data are interpretations of events by the researcher, it is necessary to validate this through interviews with relevant stakeholders. Furthermore, additional data for the three internal Niche processes can be gathered through interviews, which might prove difficult through the primary data (especially learning process and expectations). This will result in a final (validated and expanded) event graph.

The patterns that emerge from the event graph will be interpreted and linked to the criteria from the theoretical framework in order to assess the progress of the hydrogen clusters. This will be used as input for the final results and recommendations. Figure C.1 is an elaboration upon the research approach (Figure 3.5), which indicates the results that roll out of each of the steps. These will subsequently be pivotal for the successful continuation of the research.

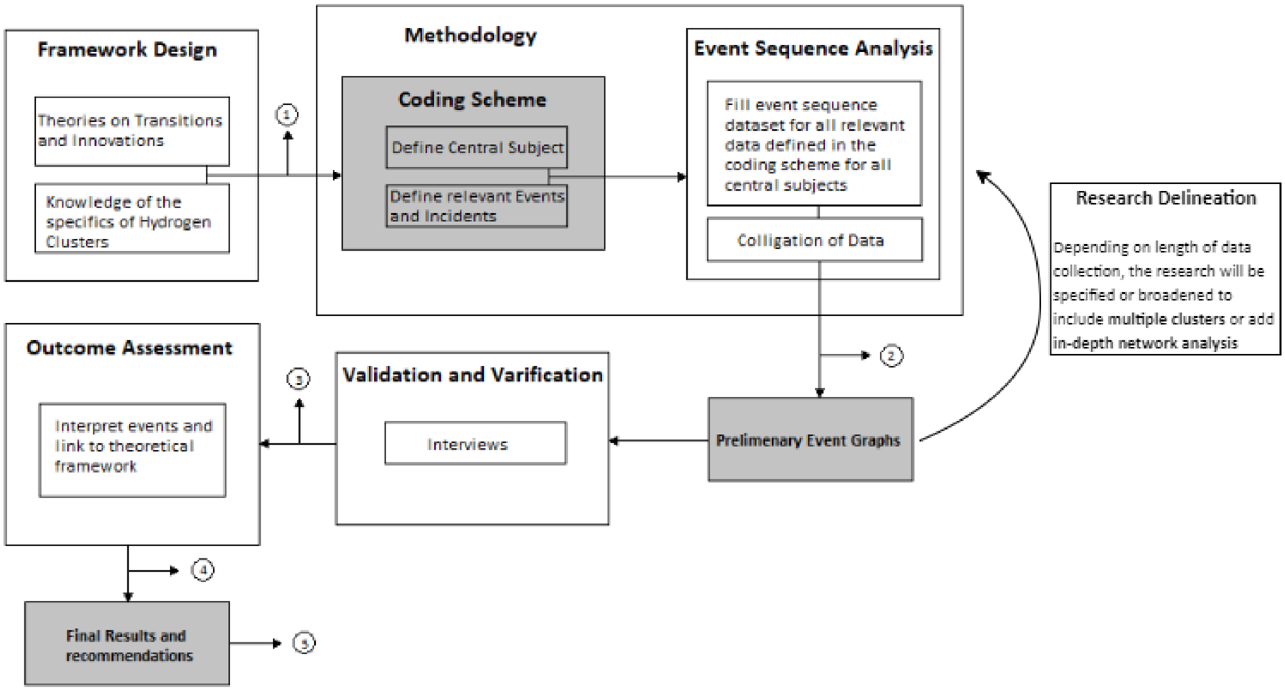

Figure 3.5: Research Approach: The numbers in circles indicate the Sub-Questions that will be answered by the previous step

3.4 Conclusion of Theory and Methods: Analysis Manual

This section is intended to serve as a guide for performing analysis of hydrogen niche implementation, based on the theoretical approach that has been described above (mainly with SNM and MLP). SNM will be used to analyze the sociotechnical dynamics and factors within the niche - in this case hydrogen in the Netherlands. This is done within the framework of the MLP, which adds to the SNM by providing more insight into the external environment in which the niche develops - in this case the energy, built-environment, transport and industry sector in the Netherlands and Dutch society as a whole (determined by a mix of TIS and MLP). Therefore, these two frameworks are combined, together with some elements that are specifically important for hydrogen in the Dutch context to provide insight into the relevant factors and how they relate to the transition path of hydrogen in the Netherlands (See Figure 3.6 for an illustration of how these two theories relate to each other).

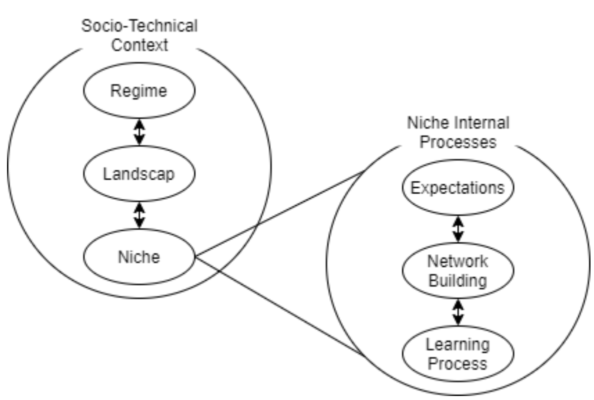

Figure 3.6: How SNM and MLP relate to the analysis

Within the methodological framework it appears important that a research approach is followed that takes the order and sequence of all relevant processes into account. As described in chapter 3, a fruitful research approach in this context is the so-called "Event Sequence Analysis", which stems from the Process perspective, which conceptualizes development and change processes as sequences of events. Through such an approach, a kind of story line can be presented of how internal niche process X influences technology development and at the same time all the other niche processes. Thus, the process approach creates valuable insight in the underlying mechanisms that determine technological change through time.

In the context of this thesis, this approach is used to map 'relevant events' that take place within the hydrogen niche in the Netherlands, where the data collection is not so much focused on following all the individual agents or innovation projects in the system, but on events that are reported at the system level. The sources are primarily collected from newspaper articles professional journals, research reports and company websites. Based on a data search, a chronological database is constructed in which all these "relevant events" are mapped. All the events that are mapped are then allocated to the criteria (incl. The three niche processes) by means of an allocation scheme.

The final outcome of the process analysis is a storyline, underpinned by several pictures where the events are plotted over time, of how the development of hydrogen niches have evolved over time and the role of the different niche processes in this development. Insights in these patterns are the first step towards policy recommendations regarding the governance of the implementation of hydrogen in the Netherlands.

The purpose of analyzing the Niche internal processes is to analyze and evaluate the development of a niche implementation in terms of the structures and processes that support or hamper it. The basic steps that are taken are shown in Figure 3.7:

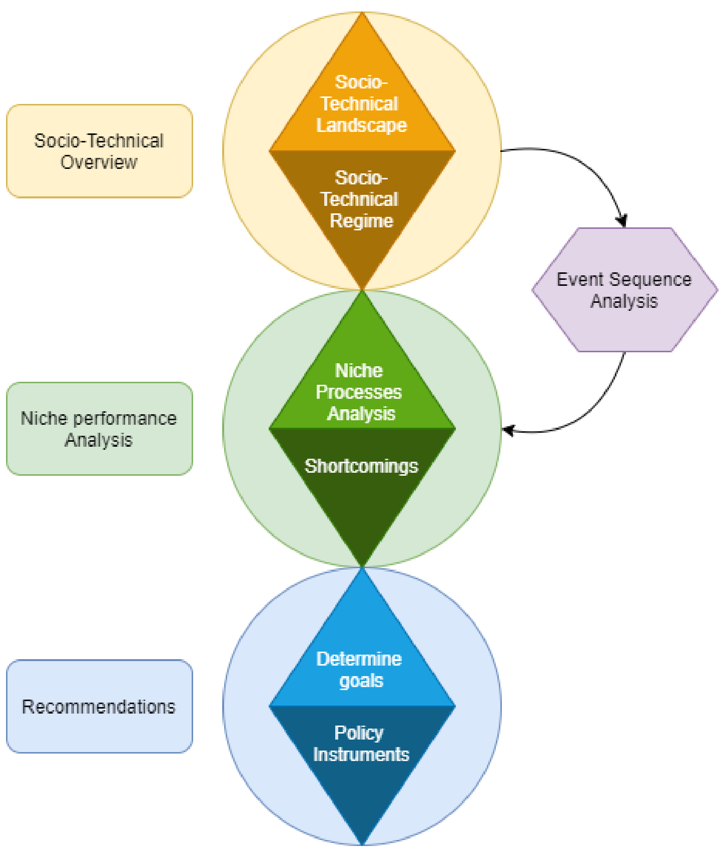

Figure 3.7: Outline of the Steps for the analysis

3.4.1 Step 1 – Socio-Technical Overview

This section presents the macro level of analysis for the in-depth case study of hydrogen in the Netherlands. In this step, the MLP framework will be applied, upon which the micro-level of analysis (SNM) will be based. It is specifically hydrogen in the Netherlands that is of focus in the data collection. However, in accordance with the proposed framework, the case study also covers broad socio-economic situation of the Netherlands and describes the socio-technical landscape and regimes. This step is necessary, since the upscaling of an innovation is not solely the result of the above described internal niche dynamics or functions, the external environment also exerts in fl uence. The MLP will be used to analyze the external developments that influence the transition path of hydrogen, since the extent to which an innovation is able to upscale, is fl uenced by the interaction between the three levels (Landscape, Regime and Niche).

The space Niches are given to claim a position within the regime is directly related to the rigidness that exists within the regime. As described in Chapter 2, the dominant actors within the regime (established order) offer resitance against niche developments. The concept of “modulation” is very important here; this means that the regime must destabilize or become weaker (from the Landscape, from internal regime tensions or from the parallel Niche developments), so that “window of opportunities” are created so that the niche can potentially have a breakthrough. When the interactions between the levels are aligned, they reinforce each other (source).

- **Indirect influence:** In this thesis I will call this process towards ‘modulation’ an indirect in influence of the regime on the niche. Regime destabilization can come from the top-down, the destabilizing Landscape pressures or by internal regime destabilizing pressure/tension. In addition, a niche can also experience internal developments through, for example, decreasing costs/increasing quality, endorsement of key actors, etc. This can lead to regime destabilization from the buttom-up (source).
- **Direct influences:** Landscape and regime developments can also have an effect on the transition path by influencing the niche internal processes. An example of this may be that the regime has a poor performance, as a result of which actors and the general public are more inclined to focus on an alternative niche (this can increase expectations). Landscape factors can also have an influence, for example through a shift in culture or an improved education system that can lead to better learning processes or attract more actors to the niche. In this thesis I will call factors that directly in influence niche processes such as network formation and learning processes direct influences.

3.4.2 Step 2 – Niche Performance Analysis

As described in Chapter 2, SMN will be used analyse to what extent ‘relevant event’ lead to learning processes and whether this leads to future adjustments in follow-up projects or investments; what the relationship is between the design of an experiment and what has been learned by different actors. The goal is to understand how the transition in the Netherlands has taken place and whether experimentation had been properly used as a basis for development and application of hydrogen. The focus of this part of the analysis is on the occurrence of the three internal niche processes (The voicing of expectations, Network formation and Learning Processes) in the progression of events and to make an assessment of the quality of these processes. SNM was developed as an analytical approach that can be used to review and analyze the development of innovative technologies in niches, which can be seen as incubation rooms or protective systems surrounding the new technology (Caniels & Romijn, 2008; Schot & Geels, 2008; Smith & Raven, 2012). Therefore, it will contribute to understanding the difficulties that the implementation of Hydrogen is facing.

In the following subsections it will be explained how the three internal niches will be analyzed, in order to answer the RQ.

3.4.2.1 Internal Niche Process 1 - Shaping and voicing of expectations

From the SNM perspective expectations guide the technological development, it attracts more resources and actors want to participate and it influences the design of projects. Also very important here are “success stories”;

these can cause expectations about a particular niche to converge and align, which in turn provides momentum for the niche upscaling. It is therefore important to identify how voices about specific niches are voiced, especially for niches that are still very much developing and relatively unproven (source). A study by Kamp (2015) showed that there is also a strong need to voice and shape expectations of actors outside the niche in order to attract these desired niche actors into the network.

At the initiation of the niche, actors are likely to join the niche by investing effort, money and time, due to positive expectations regarding the future success of the niche. At the beginning stage, actors usually have broad and unclear expectations about the technology and different visions of its future (van der Laak, et al., 2007). Over the course of time, expectations can change because of external factors (regime and landscape) and internal circumstances (e.g. results from experiments within the niche) (Raven, 2005). This distinction between **exogenous** and **endogenous expectations** is introduced to gain more insight in the origin of the expectations.

Furthermore, there is also the question to which degree expectations are shaped through niche experimentation itself or by the Regime of Landscape. Therefore, it is important to not only evaluate expectations of the niche actors (**internal expectations**) - which is traditionally done in SNM studies - but expectations of actors outside the niche are also taken into account (**external expectations**). By looking at these expectation types, something can be said about whether the transition pathway can be improved by actively trying to shape expectations of actors outside the niche, for example.

3.4.2.2 Internal Niche Process 2 - Network Formation

As described in chapter 2, Actor networks are of essence to the development of a niche, because they maintain development, attract resources and new actors, enable learning and carry expectations (van der Laak, 2007). At the initiation of a niche, the social network around the niche is pivotal, but the number of and diversity of actors is usually lackluster. Through the process of experimentation more actors can get involved, so that the network increases. The importance of increasing the amount of actor types is that it will simultaneously (usually) broaden the range of perspectives. As mentioned in Chapter 2, therefore, broadness of a social network is one of the criteria for a good quality network building process. Furthermore, the quality is also determined by the amount of interactions, since this increases the potential of convergence between actors, which will increase the effectiveness of the niche (van de Poel, 2000). Mourik (2006) add that a ‘well-functioning’ network actively fosters the coordination and convergence between varying expectations.

3.4.2.3 Internal Niche Process 3 - Learning Process

Learning encompasses a plethora of processes due to which actorscan articulate relevant technological aspects, markets and other characteristics (Wiskerke & van der Ploeg, 2004). Learning influences the niche by affecting the expectations and aligning them. A good learning process is reflexive and focuses on various different aspects (van der Laak, 2007). Furthermore, good learning processes should not be confined to individual learning by actors, but should also consist of interactive learning or, in other words, knowledge sharing among actors (Kamp, et al., 2004).

For newly emerging niche, like hydrogen, it is pivotal that good learning processes are in place. This means that learning should be broad; Not just with an emphasis on technological and financial development, but also on aligning technical with social considerations and effects. A good learning process should also apply “elasticity” by examining the fundamental social values attributed to the technology, while applying that as a feedback loop for future technological design. Additionally, the two types of learning, **first-order learning**[1] (focus on accumulation of data) and **second order learning**[2] (showing flexibility to reevaluate and challenge underlying assumptions), should be present throughout the process.

Furthermore, Hoogma (2002) distinguishes learning with regard to the following five aspects:

[1] Refers to learning about the innovation’s effectiveness in achieving pre-defined goals. It is directed on gathering facts and data.

[2] Learning about the underlying norms and values related to the new technology. This type of learning enables changes in assumptions and cognitive frames and has a larger contribution to niche development than first order learning.

- Technical development and infrastructure;
- Industrial development;
- Social and environmental impact;
- Development of the user context;
- Government policy and regulatory framework.

In this thesis, I will add one aspect to these five. I will also evaluate the learning processes regarding hydrogen potential and analysis, to evaluate to which degree actors have learned about the available hydrogen resources.

3.4.3 Step 3 – Recommendations

SNM is mostly used as a policy tool for the purpose of evaluating the existing policy and providing suggestions for the future policy making (Raven, 2005). Therefore, it is a desirable framework to provide insights into the nature of the obstacles that innovations - like Hydrogen - face and help to develop methods to overcome these obstacles (Canils & Romijn, 2008). The outcome of the previous analysis is the identification of a number of niche process criteria that can form an obstacle for the progress of technological development or the Landscape-Regime and Landscape-Niche inter-dynamics. The obstacles can block the development and diffusion of the technology and the context inter-dynamics can create windows of opportunity. In this step the causes for the hampering will be identified. The causes can origin in the socio-technical context. The niche processes that are badly fulfilled can be a manifestation of problems in the context. By identifying where the problems are within the system the barriers can be removed. If the government develops policy to improve and facilitate the implementation of the niche, then the new policy will be included in the socio-technical context, which will influence the internal niche processes of the system. The most important questions become: (1) What are the consequences on internal niche processes of the causes in the context and what are the consequences on niche processes of the competition between several Clusters? (2) Do the barriers have to do with Landscape or Regime deficiencies or with lack of internal niche quality? (3) What are the effects of the Socio-technical context on the cluster performance – which internal niche processes improve or become worse due to context problems? In order to find the causes in the context of the system the following steps will be followed (see Figure 3.8):

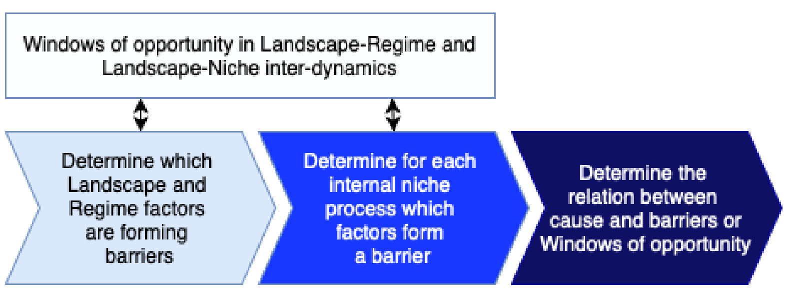

Figure 3.8: Recommendations to answer the RQ through analysis of SNM and MLP

Innovation policy is about helping companies to perform better and contributing to wider social objectives such as growth, jobs and sustainability. There are many policy tools available to achieve this, ranging from establishing supportive framework conditions (e.g. human resources, an internal market, intellectual property) to facilitating access to finance, policy benchmarking and enabling collaboration or stimulating demand, for instance, through regulation, standards and public procurement. Geographical and technological scope of the Niche under study. Therefore, it is important to determine the policy goal because new emerging energy technologies provide different opportunities which can lead to different policy goals and changes of these goals over time. For the interpretation of the results it is important to determine what the goal is. In this step the link needs to be made between the results of the analysis of the context and the fulfilment of the niche in ideal circumstances. In this step the most important barriers and windows of opportunity need to be ranked in order to provide recommendations on how to achieve the policy goal.

3.4.4 Summary of SNM analysis

Table 3.1: Summary of SNM criteria (moslty) based on van der Laak (2007)

Niche Process	Quality	Criteria
Voicing of expectations	Robust	Supported by more actors
	Focused	Clear and specific goals
	high Quality	Supported by sufficient evidence
Network Building	Semi-Functioning	If diverse actors participate
	Highly-Functioning	More diverse actors participate and alignment between actors
Learning Process	Sufficient	Includes both first-order and second-orde learning

3.4.4.1 Summary of internal niche event sequence analysis

Niche Process	Incident	Analysis of
Voicing and shaping of Expectations	Exogenous Expectations	Expectations originating from developments that are external to the niche expectations: landscape and regime factors.
	Endogenous Expectations	Expectations originating from learning experiences and network composition within the niche.
	Internal expectations	The quality, robustness and specification of expectations of the current actors in the niche.
	External expectations	The awareness and confidence level of actors outside the niche.

Niche Process	Incident	Analysis of
Network Building	Network composition	The desired network composition and network completeness.
	Network interactions	How and to which degree the network actors are interacting.
	Network alignment	The degree to which actors' vision, expectations and strategies are in line with the niche development.

Niche Process	Incident	Analysis of
Learning Process	Technical development and infrastructure	the learning about design specifications, complementary technology and the required infrastructure needed for technology dissemination.
	Industrial development	The learning about the production and maintenance network needed to broaden technology dissemination.
	Social and environmental impact	The learning about the technology's impact on safety, energy and the environment.
	Development of the user context	The learning about the end-user characteristics, their requirements, their barriers for technology adoption and the meanings they attach to a new technology.
	Government policy and regulatory framework	The learning about the institutional structures and legislation that are relevant for dissemination, and the incentives they can provide to encourage adoption.
	Hydrogen potential and analysis	The learning about the available hydrogen resources.
	Appropriate business models	The learning about business models that enable successful market penetration.

Illustration of the SNM analysis
Figure 3.9 illustrates the aspects that will be taken into account in the SNM Analysis in chapter 5, with an explanation of the concepts in Table 3.4.4.1.

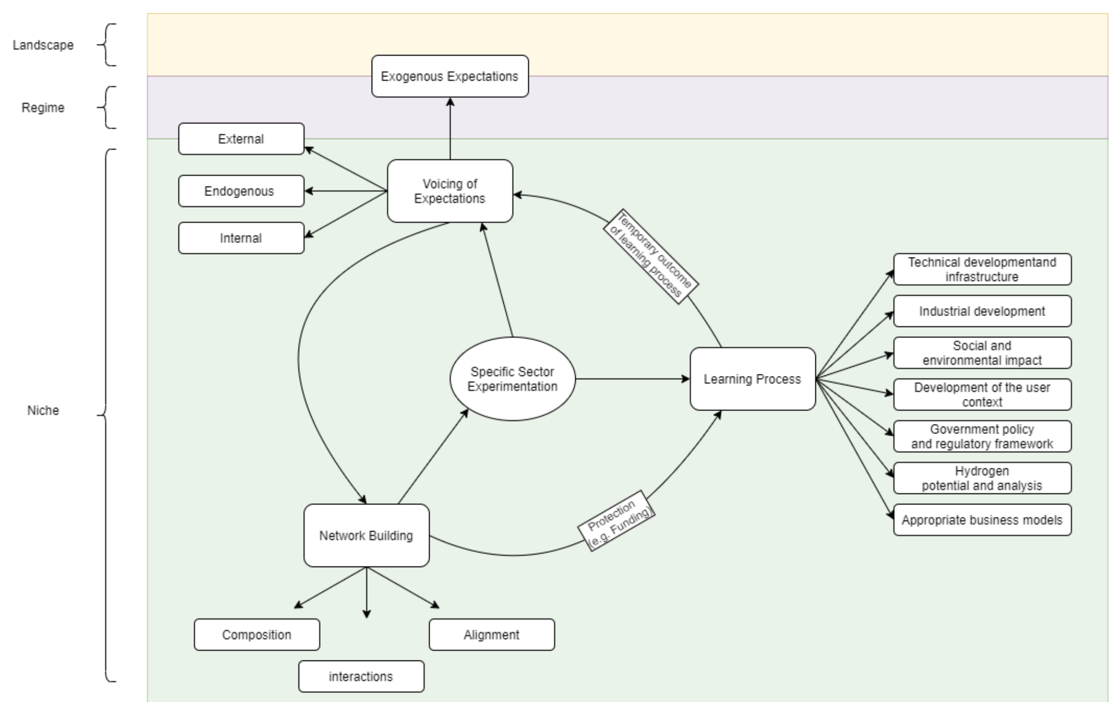

Figure 3.9: Illustration of the SNM analysis manual

Chapter 4

Event Sequence Analysis of the Transition Pathway of Hydrogen (Clusters) in the Netherlands

This Chapter covers the Event Sequence Analysis (ESA) as discussed in Chapter 3. As mentioned in that chapter, the coding scheme for this analysis stemmed from the conceptual framework developed in Chapter 2. This chapter starts with an exploration of the key landscape events, then the conceptual delineation of hydrogen clusters is covered, then the Event Map is discussed, with a description of the events per pre-determined relevant sector and lastly the barriers which have been found are laid forth in the final section.

4.1 Socio-Technical Landscape Developments

The historical development of hydrogen as an energy carrier spans back to 1520 when the element was first discovered (Wylie-Interscience, 2005., pp. 797–799). This developed slowly through the decades, which led to the invention of the first fuel cell in 1842, which was at first seen as not practically useful until the mid 1900s. It was only in 1959 when the first practical demonstrations came of a 5-kW alkaline fuel cell and a 15-kW fuel cell used in a tractor (Emsley, 2001). Afterwards broader interests in fuel cells increased culminating in NASA's use of them in aerospace in the 1960s (See Appendix C.3 for more details on the early historical development) (ibid.). After this initial discovery and preliminary development of hydrogen and its potential applications (1520 - 1970), the Socio-Technical Landscape developments can be categorized in three main periods: (1) The period which was initiated by the oil crisis in 1970, which led to a renewed search for alternatives to fossil fuels (1970 - 2000), (2) the period after the 9/11 attacks in 2001, which led to a movement towards less dependence on OPEC (2001 - 2012), (3) and finally the Climate movement, which has a longer history, but became highly influential (to hydrogen) around the signing of the Dutch SER accord in 2013 (2013 - 2020).

4.1.1 Oil Crisis leads to search for alternatives (1970 - 2000)

The oil crisis of the 1970s led to a renewed search for alternatives to fossil energy (oil). During this time, the phosphoric acid fuel cell is also being developed (with a phosphoric acid electrolyte). The term "hydrogen economy" also emerged in the 1970s. Coined by John Bockris in 1972, this term describes the energetic, ecological, and economic aspects of an ideal energy system – without dependence on petroleum and emission-free - based on hydrogen (Bockris, 1977). While this idealistic image, on the one hand, appealed and motivated a group of people, including scientists and policymakers, this ideal image has probably also contributed to a degree of skepticism in another group. This contrast can be observed to this day. In the 1980s, 1990s, and 2000s, there was a slow development of hydrogen technology. In the 80s, fuel cells are used by the US Navy in the Deep Quest submarine, in the 90s the first larger stationary fuel cell plants (order 250 kW) are placed for commercial and industrial applications (NASA, 1990).

4.1.2 Movement towards less dependence on OPEC (2001 - 2012)

In the 2000s, a kind of expectation arises ("it is almost there"); on the other hand, developments took longer than expected. The lifespan of the materials remained too short, and the costs too high. This also causes a kind of wave movement in social and political interest, resulting in fluctuating subsidy flows. In the Netherlands, this even led to the cessation of almost all activities related to research and development of hydrogen technology in (semi) public institutions around 2008 (until after 2012). ECN is the clearest example of this, where full research into hydrogen technology was discontinued in 2009 (ECN, 2012). In the United States, on the other hand, large-scale investments were made during the same period. Since the attacks on September 11, 2001, hydrogen has been referred to as freedom fuel in the United States because it would reduce dependence on OPEC (The Wallstreet Journal, 2003). As a result, President George W. Bush announced the "hydrogen fuel initiative" worth US $1.2 billion in 2003 (The White House, 2003). As a consequence, he transferred much of the US renewable energy budget to research related to the hydrogen economy. In 2008, the hydrogen technology grant program in the United States consisted of US $228 million (approximately 50% of the total budget for energy efficiency and renewable energy).

Japan also invested on a large scale in the development of the technology during this period. From the end of the last century, large car manufacturers are also starting to set up increasingly larger R&D departments around fuel cells and to develop the first prototypes (Japan Times, 2007). In 2008, the Honda FCX Clarity became the first fuel cell electric car to be leased. In 2009, a major program for implementing residential cogeneration (CHP) plants for heat and electricity generation with fuel cells in homes started in Japan (Panasonic, 2013). As a result, more than 120,000 of these micro-CHP units are currently installed in Japan. the first 1 MW fuel cell power plant in Belgium in 2012 with membrane technology (PEMFC). In 2014, the US FuelCell Energy in South Korea installed 59 MW of fuel cell plants with molten carbonate technology (MCFC). At the end of 2016, there were 390 stationary fuel cell plants in the United States with a total capacity of 275 MW. Scaling was also being done with regard to electrolyzers: In 2016, Siemens reports that it has developed a large-scale 50 MW electrolyzer, aimed explicitly at large-scale electricity storage in, for example, power-gas and power-to-hydrogen.

The Toyota Mirai, a commercial hydrogen-powered passenger vehicle, will be available in 2014 and the Hyundai IX35 in 2015 (Hyundai, 2014). Worldwide, 2,555 hydrogen-powered vehicles were already in operation around the end of 2016, of which 1295 in the US alone. Of course, compared to battery-electric transport, this was only a small proportion, since commercialization started 20 years later. Of the 2555 hydrogen-powered vehicles, 2184 were passenger cars (1397 Toyota Mirai; 457 Hyundai IX35) and 135 hydrogen-powered buses. In Figure 4.1 a broad overview of the sequences of events of the more recent development of the idea of the hydrogen economy is summarized from around the 1970s, when the idea first emerged.

4.1.3 (Dutch) Climate Movement (2013 - 2020)

The period 2005-2017, the Netherlands' CO_2 emissions remained at around 180 megatons per year (10 tons per person), as opposed to 160 Mt in 1990 (Muntean et al., 2018, p. 161). The Paris Climate Goals (2015) dictated that 14% of the energy had to be renewable in 2020 and 16% in 2023. The climate act of may 2019, further stipulated that GHG emissions would be reduced by at least 49% in 2030 and by 95% in 2050 compared to 1990 (Rijksoverheid, 2019). Nevertheless, in 2020, the percentage remains at 9%, the 2nd lowest percentage in the European Union (EU) (Sociaal-Economische Raad, 2013). In light of this, and according to calculations by PBL, the goals were most likely not going to be achieved (PBL, 2019). Because of this, the national government is promoting wind energy; in 2016 they announced that 7,000 MW offshore wind farms would be built in the period 2024–2030 (Rijksoverheid, 2016). This led to the accumulation of approximately 1 GW off-shore wind turbine capacity in 2019 (CBS, 2019). The goal was that around 2023, at least 4.5 GW off-shore windpower would be installed (3.3% of all energy) and 11 GW in 2030 (approximately 8.5% of all energy and approximately

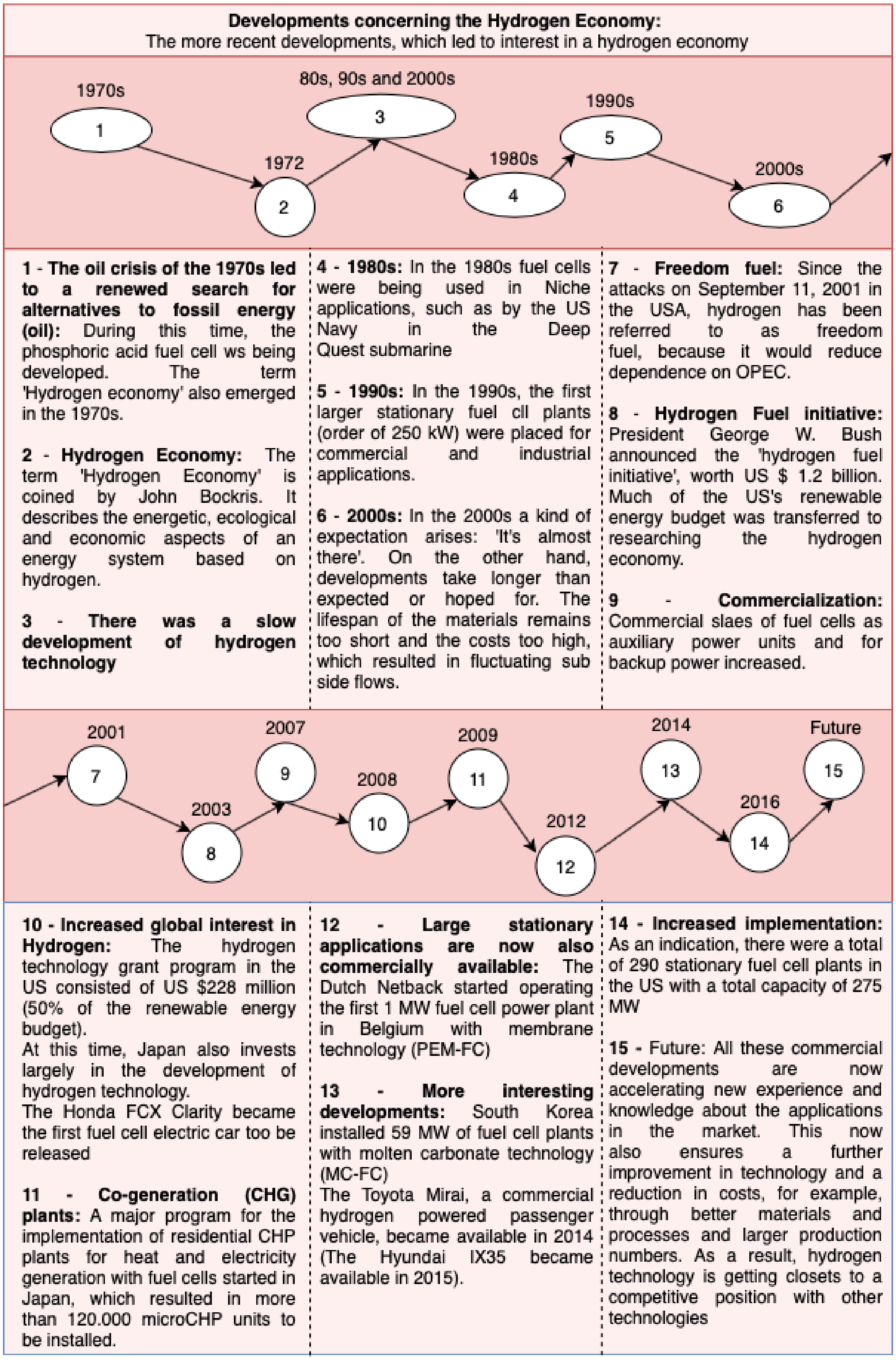

Figure 4.1: Developments concerning the hydrogen Economy (1970 - 2020)

40% of the current electricity consumption). Solar energy was also growing rapidly; In 2018, 1.4 GW PV panels were installed, which increased the total power to 4.3 GW. In that year, 3.15 TWh PV energy was produced (3% of the total electricity consumption) (ibid.). In Feb 2018, the Rutte III cabinet determined to phase out the natural gas extraction in Northeast Groningen and to discontinue it around 2030 (De Volkskrant, 2018). It stipulated on May 18, 2018, that the two oldest coal-fired power plants in the country, the Amer power plant and the Hemweg power plant, had to switch to a sustainable fuel by 2024. The same applied to the newly built coal-fired power stations on the Maasvlakte and in the Eemshaven as of 2029. On the 21^{st} of December 2019 it was announced that the Centrale Hemweg 8 would be closed within a few days (NRC, 2019). According to the National Climate Agreement (June 2019), the European Commission wanted to argue for 55% less greenhouse gas emissions by 2030, more than the 49% basic package (European Commission, 2019). This meant that the Netherlands would have to set even more ambitious climate goals in all relevant sectors (Built Environment, Mobility, Electricity and Industry).

The draft climate agreement - a comprehensive package of agreements, measures and instruments that should reduce Dutch CO_2 emissions by at least 49 percent by 2030 - also assumes an important role for CO_2-neutral hydrogen in the energy transition. It contains various measures to bring the 2030 CO_2 reduction targets closer to industry, the electricity sector and mobility with green hydrogen (See Appendix C.2). The climate agreement includes an ambition of 500 MW electrolysis in 2025 and 3-4 GW in 2030 (Rijksoverheid, 2019). The Climate Agreement also points out that hydrogen can fulfill a number of essential functions in the Dutch energy system. Firstly, it states that it is necessary to determine in 2021 how much extra sustainable electricity must be provided to meet the extra demand for electricity through hydrogen and electrification. In addition, the program will focus on the development of an optimal hydrogen infrastructure (ibid.).

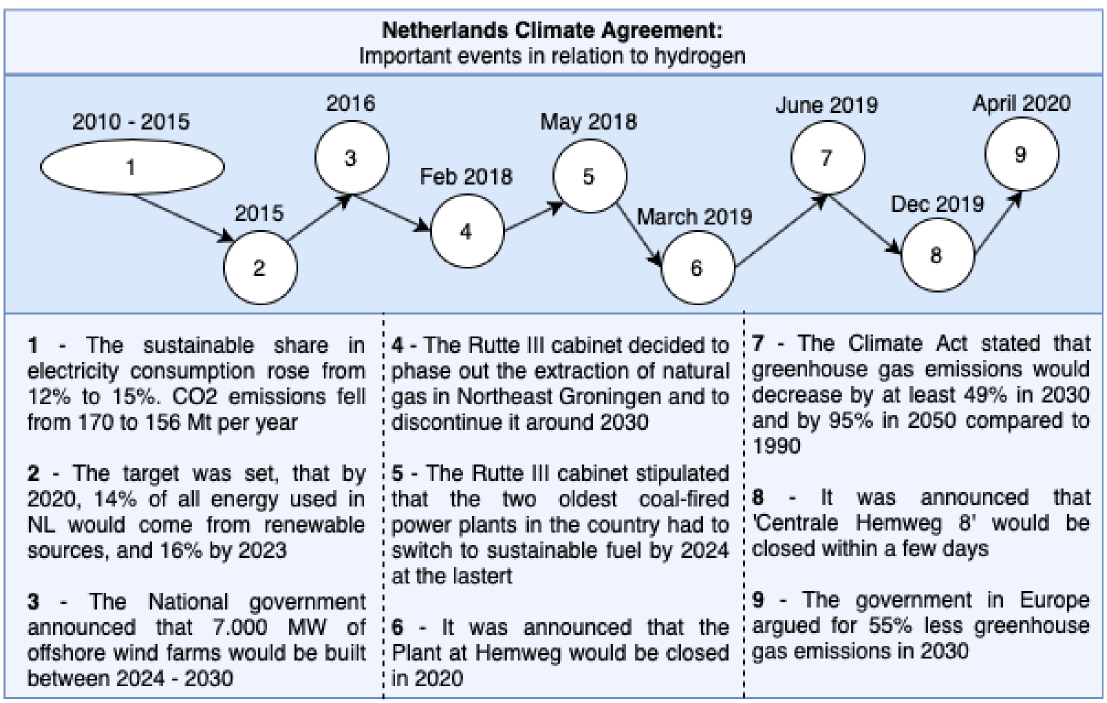

Figure 4.2: Important events in relation to hydrogen from the Netherlands Climate Agreement

4.1.4 More General Hydrogen-related developments (2000 - 2020)

In the 1970s and early this century, for example, there was regular attention for CO_2-neutral hydrogen as a future energy source with great potential. At the beginning of 2004, the book The Hydrogen Economy (NRC, 2003). In the same year, the VPRO devoted extensive attention to the hydrogen revolution (VPRO, 2004). At that time, the emphasis was strongly on the use as fuel for fuel cell cars. After that it remains relatively quiet because this technique still had many challenges. In May 2018, the Hydrogen Coalition - a group of 27 environmental organizations, knowledge institutions, governments and companies - advocated a concrete program for hydrogen in the climate agreement (Waterstof Coalitie, 2018). In 2019 VPRO made a new Tegenlicht, called delta plan for hydrogen, with the theme: “Can we use the existing gas network for green hydrogen if the Netherlands goes away from natural gas?”; CO_2-neutral hydrogen was back on the agenda as a result of discussions about climate change.

Business organization VNO-NCW labels “Green hydrogen as an engine for growth and greening” and already calls the Netherlands Hydrogen Country (VNO-NCW, 2018). The entrepreneurs want to work with the government on a sustainable and above all attractive future. In 2017, the Ministry of Economic Affairs and Climate asked the Top Consortium for Knowledge and Innovation TKI New Gas to take the lead in drawing up a roadmap for hydrogen (Energeia, 2017). The minister noted that the theme of hydrogen was gaining increasing interest. The publication was completed in May 2018 and concluded: “Hydrogen is important to be able to realize the social task of drastically reducing CO_2 emissions. It is a robust option that has many production and application possibilities and fulfills a system role. Hydrogen can contribute to all transition paths (TKI Gas, 2017).” In November 2019, the Hydrogen Coalition made a new appeal to the government and the House of Representatives to prioritize hydrogen as an essential building block for the energy transition (Waterstof Coalitie, 2019). In addition, they called on the company to ensure that, by 2025, there is at least 500 megawatts of installed electrolysis capacity to achieve the ambition for hydrogen in the Climate Agreement. This first step in the up-scaling of green hydrogen also offers sufficient prospects for the market with a view of 3-4 GW installed capacity in 2030. This means that the climate targets remain within reach.

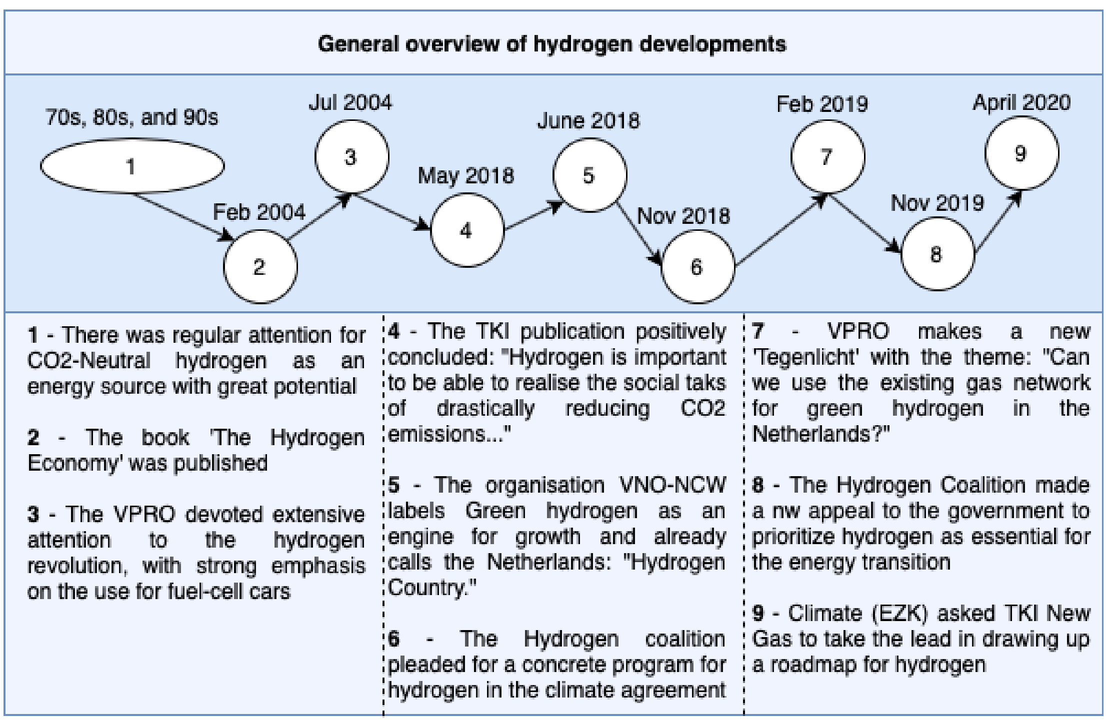

Figure 4.3: General overview of hydrogen developments

4.2 Hydrogen Cluster Delineation

Hydrogen clusters are usually a collection of players from different aggregation levels, from niche actors to established regime players; this makes them hard to position within the MLP. According to McCauley and Stephens (2012), such clusters are arguably positioned between the niche and regime level. Because of this unique positioning, hydrogen clusters can both foster as well as constrain regime-level change. By taking into account, the MLP framework on hydrogen clusters, the role of established players that are encompassed within the clusters can be taken into account. The literature also clearly indicates that governments play an essential role in the success or failure of setting up new cluster initiatives (Ketels et al., 2006; Lindqvist & Sölvell, 2006; Wandel, 2009; Fornahl et al., 2010). Despite this observation, little attention has been paid to the role that clusters play in influencing policies and institutions that form barriers (Hermans, 2018). For this, too, the MLP can enrich the research of hydrogen clusters.

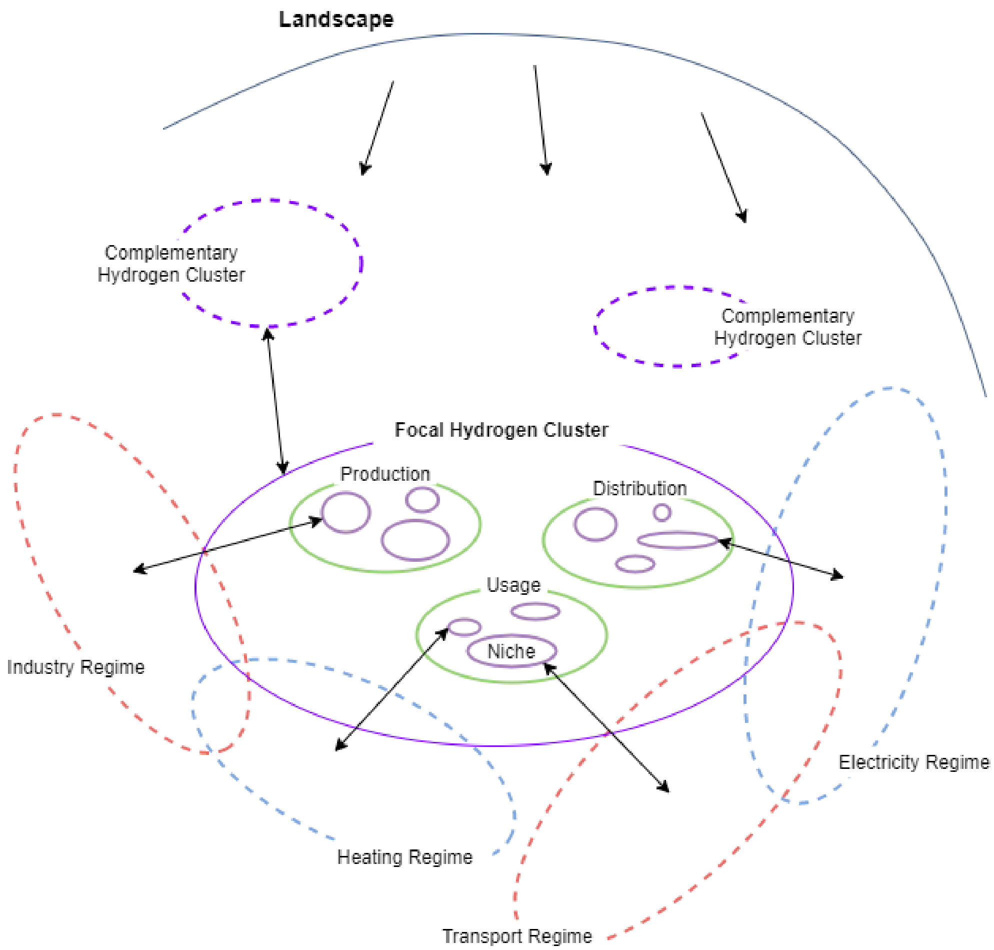

Figure 4.4: Hydrogen Clusters delineation from a transitions theory and a Technological Innovation System perspective (Adapted from Markard & Truffer (2008))

As discussed in Chapter 2, hydrogen as a molecule can be used for a plethora of end-uses, in a multitude of sectors/industries and on different scales. Its uses range from raw materials for the manufacturing of products, combustion for industrial heating, electrolysis (or Natural Gas Reforming/Gasification) on a large scale for storage of excess renewable energy, or a smaller scale as a fuel in hydrogen fuel-cell cars. In order for the technology to be scaled up, production should also be increased, and infrastructural changes will also play a significant role (and could be a bottleneck). The delineation according to the proposed TIS framework of Markard and Truffer (2008), which merges these two fields (MLP and IS), ensures that the whole of the hydrogen innovation system can be taken into consideration and thus ensure that all regimes (industry, electricity, transport and (heat for) built environment) that are of influence are taken into consideration. Markard and Truffer (2008) also state that such a TIS includes different niches but it is more than the sum of the niches, which has been uncovered to be pivotal with the hydrogen niche (See Chapter 2).

Figure 4.4 shows the delineation of a Dutch Hydrogen Cluster with the use of this framework. The Figure illustrates the aspects of the hydrogen cluster that will be taken into account. The two-sided arrows illustrate that four major regimes influence and are influenced by Hydrogen-based Niches. Furthermore, the regimes overlap with the hydrogen Cluster as well as with other regimes. This is because certain regime actors are also key players within a specific Cluster (e.g., Gasunie (Heating regime)) is experimenting with Hydrogen production as well as with Hydrogen Usage in the form of storage. For the sake of visibility, not all connections are made in the image, but actors within different regimes have connections with multiple aspects of the supply chain. It is pivotal that events from multiple regimes are taken into account since they all influence the internal Niche processes (especially expectations). As shown in Figure 4.4, there are complementary Hydrogen clusters that influence the focal hydrogen cluster and vice versa (E.g., the Northern-Netherlands cluster and South-Holland Clusters can mutually influence each other). Finally, Landscape shifts or (stabilizing/destabilizing) pressures influence all of the above (Regimes and Niches).

Furthermore, as explained in Section 2.2.5, the niches that form within the clusters will be analysed with the SNM theoretical approach. Effective experimentation needs to exhibit networking, expectations, and learning within and across the different production stages. It is pivotal that all three aspects of the supply-chain simultaneously show good niche performance; therefore, a distinction is made in Figure 4.4.

4.3 Event Sequence Analysis for the emerging hydrogen transition in the Netherlands

Hydrogen has been widely used in the Dutch (chemical) industry for many decades. This has led to the Netherlands becoming the second largest producer of gray hydrogen in Europe (after Germany) (see Chapter 1). This hydrogen is mainly produced using natural gas via SMR (Steam Methane Reforming), where the CO_2 released is not capture (grey hydrogen). These developments were more or less separate from the more recent developments regarding (green) hydrogen, which are being done in the context of sustainability. In the 1970s, 1980s and 1990s and at the beginning of this century, some attention was already being paid to CO_2-neutral hydrogen as a future energy source with great potential, but these events were sporadic and mostly done by actors on their own initiative (without government backing) or they were exploratory experiments (with government backing) that showcased the infancy of the energy carrier and made actors dismiss it. It was not until the beginning of the 2000s, especially after the book The Hydrogen Economy was published in 2004 when globally more attention was being paid to the energy carrier once more. The same counted for the Netherlands, where in the same year (2004), the VPRO devoted extensive attention to the hydrogen revolution. At that time, the emphasis was strongly on the use as fuel for fuel cell cars. After that it remains relatively quiet because this technique still had many challenges.

It is exactly from the point where hydrogen got revisited, around the year 2000 where the focus of this thesis lies, with a separate focus on the four main sectors that are influenced by and are of influence on the transition, therefore initiatives (events) are ordered per sector (See Figure 4.5)[1] Furthermore, Figure C.4 illustrates the necessity of simultaneous niche implementation within all these sectors for the necessary uptake in the Regime, from an MLP perspective.

[1]Electricity and Built environment are grouped together due to their immense interrelatedness, since they serve the same energy function (Power-to-Gas for sustainable energy) as well as a lack of events in the Built Environment, due to the infancy of the transition in this sector.

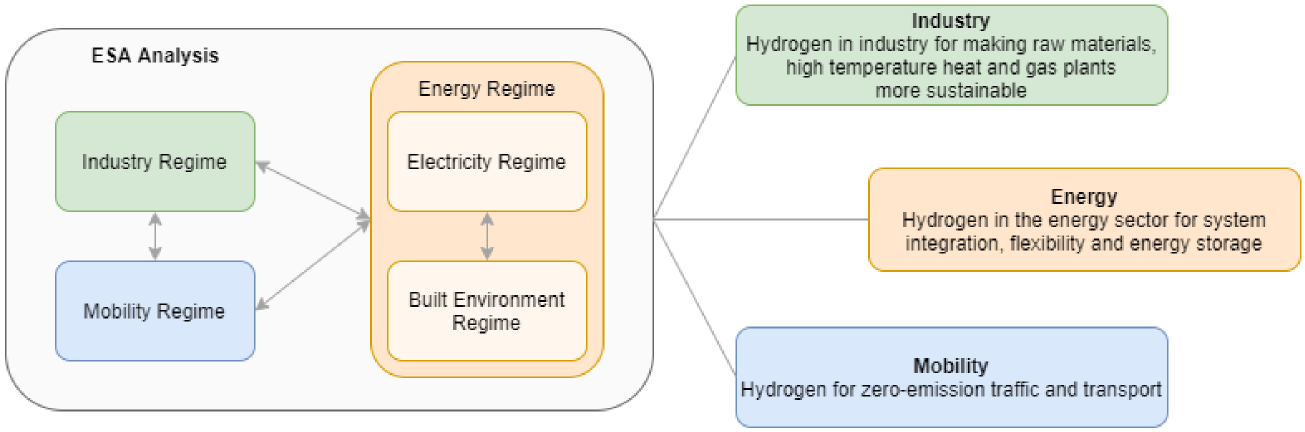

Figure 4.5: Color Coordinated delineation of the sectors that are distinguished for analysis, as depicted in the Event Maps. The differentiation between sectors is based on the energy functionality.

With the ESA, a large part of the significant socio-technical hydrogen events (related to SNM) in the Netherlands were identified through desk research, which were validated through interviews with industry experts. An 'event' in this context should be understood as an activity undertaken by an individual or a group aimed at producing, distributing, or using hydrogen as an energy carrier. This inventorying of events from 2000 to around 2020 has led to the following chronological Event Map (Figure 4.8), which can be interpreted as a sort of 'storyline' of the conceptualisation of the transition pathway of Hydrogen in the Netherlands in all relevant sectors. Events that are currently in progress, that have recently been completed, and those in the idea or planning phase were all included. Due to the importance of Regime and Landscape developments, European projects with Dutch partners are also mentioned and some European projects that have had a significant impact on development in the Netherlands. Sporadically, some global projects have also been taken into account, if they deemed relevant for the transition in the Europe or the Netherlands specifically.

The Event Maps were coded in a dedicated software (insert name). After coding the relevant events within all levels of the MLP and for all of the relevant sectors (from primary data) a raw event map was plotted with 141 events. In the coding process, the linkages between events were primarily chronologically done (per sector) and direct linkages were made in follow-ups, if previous events were explicitly mentioned, or if the linkage could be inferred implicitly due to an obvious connection (e.g., the involvement of specific actors). After a first round of separating sectors, the (raw) preliminary event map of Figure 4.6 was plotted. Within the coding process, events were differentiated by sector and level of MLP, therefore, in a second round, the event map was subdivided in accordance to the multi-level perspective as described in Chapter 2 (see Figure 4.7). In a final round of coding, and after validation interviews, the most relevant events were filtered out and illustrated in Figure 4.8.

Figure 4.8 gives a general idea of the transition pathway of hydrogen in the Netherlands. In this Chapter, the linkages between events will described in-depth per predefined sector. With the description of the sequences of events there is a focus on the theoretical framework described in Chapter 2 with a focus on concepts from the MLP (Landscape, Regime and Niche) and SNM (Expectations, Network Building, Learning Processes) frameworks. An explicit focus is on the analysis manual that has been described in Section 3.4. Therefore the aforementioned terms will be prominent in the description or a implicitly referred to, due to the nature of the coding process, where a focus lied on these concepts. After the descriptions in this chapter, an in-depth analysis will be done of the internal niche processes in Chapter 5 (using SNM).

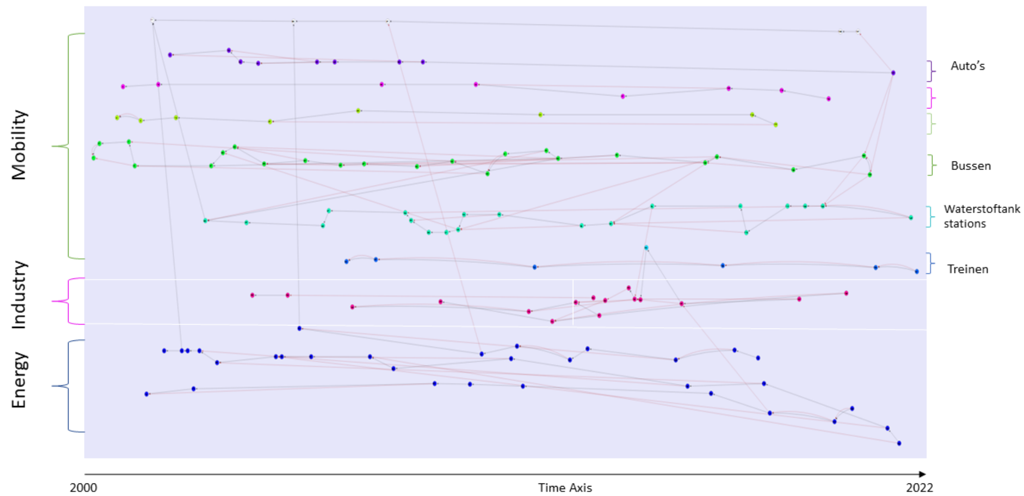

Figure 4.6: Raw Event Map with Approx 150 events that encompass the Dutch hydrogen transition in the Netherlands (2000-2020), with a differentiation in color according to each sector

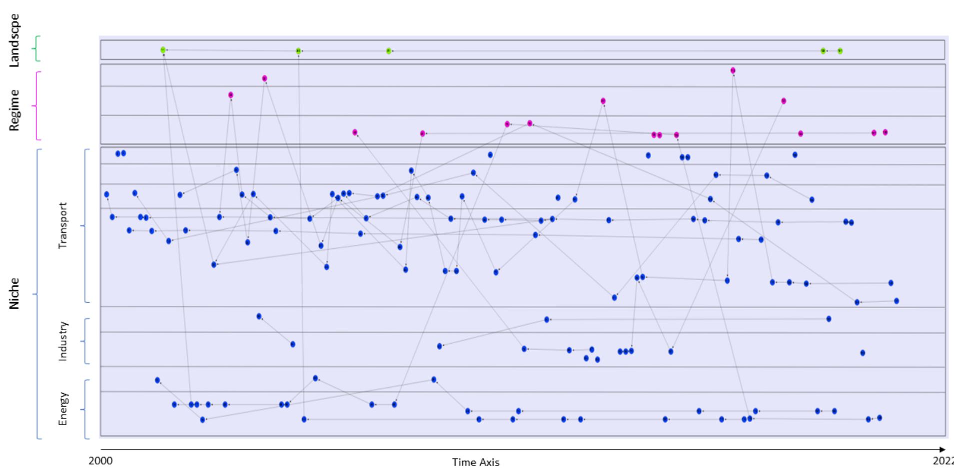

Figure 4.7: Raw Event Map with Approx 150 events that encompass the Dutch hydrogen transition in the Netherlands (2000-2020), order within the MLP, with a differentiation in color according to each level of aggregation

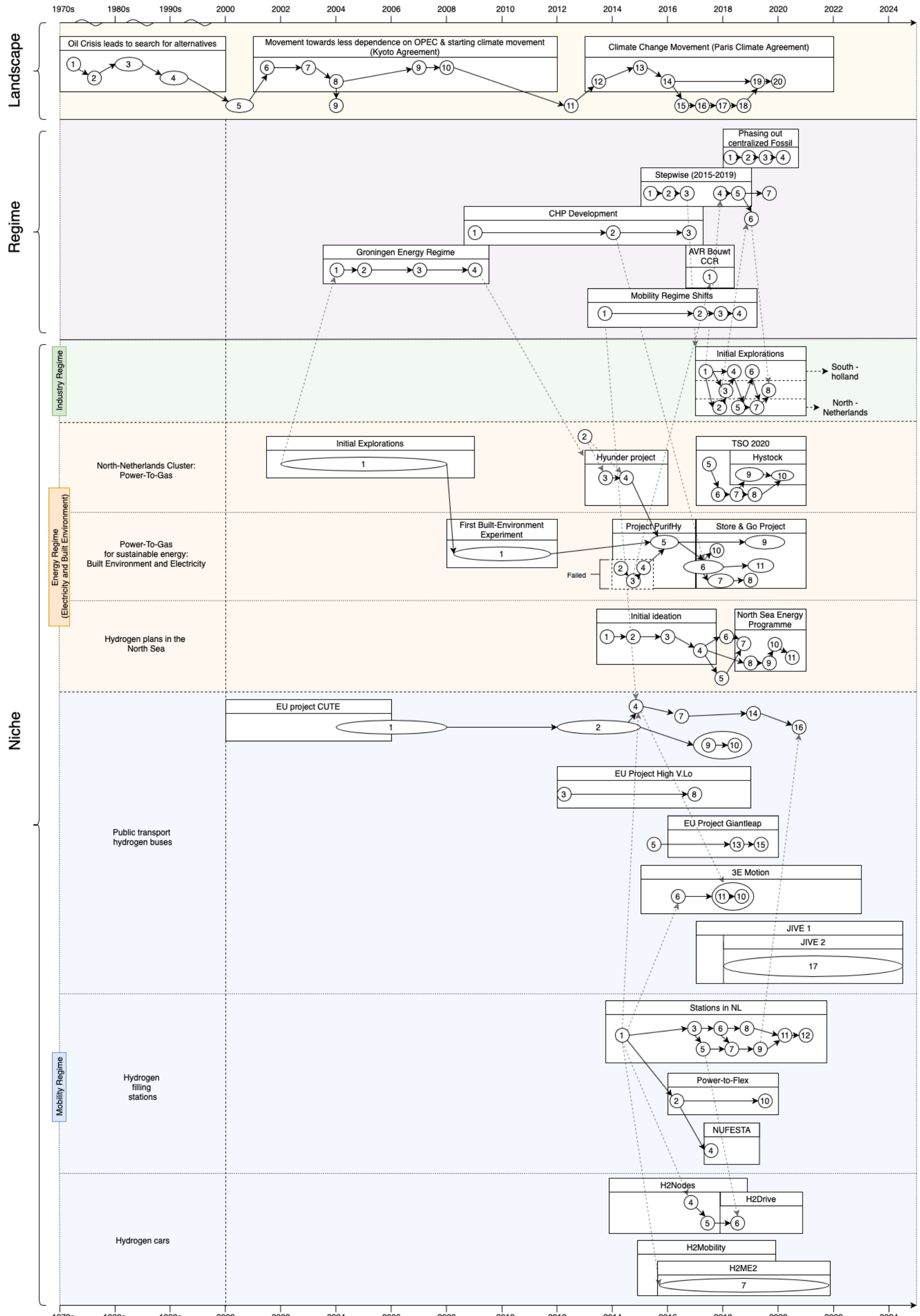

Figure 4.8: Event Map of all relevant sectors

Landscape

Oil Cisis leads to search for alternatives

1 - 1970 - Oil Crisis
2 - 1972 - Term Hydrogen Economy is coined
3 - 1980s - Fuel cells are used in Niche applications
4 - 1990s - First large stationary fuel cell plants are placed for commercial and industrial applications
5 - 2000s - Expectation arises that 'It's almost there', but still significant technical barriers

Less dependence on OPEC (mainly pushed by USA)

6 - 2001 - 9/11 attacks, making hydrogen be referred to as freedom fuel in the US
7 - 2003 - President George W Bush announced the "Hydrogen Fuel initiative" worth $1.2 billion.
8 - 2004 - The book Hydrogen Economy is published & VPRO tegenlicht
9 - 2007 - Commercialization of fuel cells
10 - 2008 - Increased Global interest
11 - 2012 - Larger stationary applications are now also commercially available

Climate Change Movement

12 - 2013 - Energy Agreement for sustainable growth (SER)
13 - Dec 2015 - Paris Climate Agreement
14 - 2016 - Announcement that between 2024-2030 7,000 MW of wind comes out to sea
15 - May 2018 - Publication `TKI - Routekaart Waterstof'
16 - June 2018 - VNO NCW - 'Green hydrogen as engine for growth'
17 - Nov 2018 - Hydrogen Coalition calls for a concrete program for hydrogen in the climate agreement
18 - Feb 2019 - `Tegenlicht' - Deltaplan waterstof (VPRO)
19 - May 2019 - First Chamber approves climate law
20 - June 2019 - National Climate Agreement

Regime

Groningen Energy Regime Developments

1 - 2004 - "Energy Valley" is established.
2 - 2005 - The Ministry of Economic Affairs is granting a EUR 2.2 million subsidy to build ten natural gas pumps in the Northern Netherlands.
3 - april 2007 - Nuon signed an agreement on CO2 capture.
4 - 2008 - Essent and Shell are considering building a power plant with CCS.

Phasing out centralized Fossil

1 - March 2018 - Announcement of phasing out natural gas in Groningen
2 - May 2018 - Announcement that coal-fired power plants are closing
3 - March 2019 - Announcement that Centrale Hemweg would be closed
4 - Dec 2019 - Hemweg 8 (Coal power-plant closed)

Stepwise (2015 – 2019)

1 - Mei 2015 - ECB tests hydrogen reactor at a steel plant in Sweden.
2 - Okt 2015 - DNV GL develops a feed-forward fuel-adaptive burner system
3 - June 2016 - Feasibility study by Statoil for a full scale CCS project in Norway.
4 - Sept 2017 - In Germany, Shell will install a 10 MW electrolyser from ITM Power at its oil refinery near Cologne.
5 - Okt 2017 - H-vision feasibility study starts
6 - Dec 2018 - Wadden Fund invests EUR 11 million in greening chemistry
7 - June 2019 - Construction of the REFHYNE 10 MW hydrogen electrolysis plant at the Shell Rheinland refinery.

Industry

1 – June 2016 – CCS Noorwegen project from Statoil
2 – Dec 2018 – Waddenfonds invests in Groningen

CHP Developments

1 - 2009 - In Japan, Panasonic accounts for half of the roughly 200.000 micro-CHPs with natural gas reformer and fuel cell installed there since 2009
2 - 2014 - Germany became Panasonic's first overseas market for home fuel cells through a partnership with Viessmann
3 - June 2017 - WKK introduction in Europe

Mobility Regime Shifts

1 – Nov 2014 – Subsidy from the ministry of I&W
2 – 2016 – Plans to make all buses emission-free in the near future
3 – Dec 2017 – Dutch Norm for filling stations
4 – July 2017 – Concession
5 – Sept 2018 – Ten-T Financing

Niche

Industry Incidents: South-Holland Cluster

1 - Feb 2017 - The Power-2-Gas-2-Refineries project examined what is needed to realize a 20 MW electrolysis installation
4 - Dec 2017 - Entrepreneurs on Goeree-Overflakkee including Proton Ventures want to use generated renewable energy (on an island) to make green ammonia.
6 - Feb 2018 - In Rotterdam AkzoNobel is working on Waste-to-Chemicals with supply of hydrogen for production of methanol with carbon (CO) from waste gasification.

Industry Incidents: North-Netherlands Cluster

2 - Jul 2017 - Nuon wants one of the three units of the Magnum power plant in Eemshaven to be converted to blue hydrogen
5 - Jan 2018 - AkzoNobel and Groningen Seaports are considering one application for funding from the Wadden Fund for a Hydrogen Innovation Park in Delfzijl
7 - Mei 2018 - AkzoNobel works with Groningen around Delfzijl Seaports on a "backbone" for hydrogen.

Industry Incidents: General

3 - Nov 2017 - Berenschot and TNO have performed a feasibility study on blue hydrogen with precombustion CCS
8 - Jan 2018 - AkzoNobel is engaged in a strategic reorientation where it wants to acquire a great position as a producer of green electrochemical products in addition to producer of chlorine and lye.

North-Netherlands Cluster: Power-To-Gas

Initial Explorations

1 - 2002 - Gasunie starts research, subsidized by the government, to use hydrogen as a fuel

Hyunder Project

The first large-scale study of hydrogen storage in Europe.

2 - June 2013 - Groningen Delegation visits Audi's Methane gas plant in Werlte, Germany.
3 - Oct 2013 - Groningse think tank presents a plan for a second gas revolution
4 - Maart 2014 - Groningen looks into the possibility of Power-to-Gas with Audi

TSO 2020

5 - Feb 2017 - Start of TSO2020 with the aim of helping to kick-start the hydrogen supply chain to mobility.
6 - April 2017 - Energystock explains that they want to build a power-to-gas installation at gas buffer Zuidwending.
7 - July 2017 - Publication of the report: "The effects of hydrogen injection in natural gas networks for the Dutch underground storages
8 - Juni 2018 - Energystock is developing the hydrogen storage so that there is a supported design.

Hystock

9 - June 2017 - Gasunie is officially pursuing the development of a power-to-gas installation near Zuidwending in Groningen.
10 - Nov 2018 - The installation started end of 2018 and construction has been finished in May 2019, with the official opening in June 2019.

Power-to-Gas for sustainable energy: Built Environment and Electricity

First Built-Environment Experiment

1 - 2008 to 2012 – Stedin Conducted tests on Power-to-Gas in Ameland

Project PurifHy (Jan 2014 – Dec 2016)

This project is investigating the possibility of selectively removing hydrogen from the sustainable gas flow.

2 - April 2014 - Ten parties sign a letter of intent to build an integrated Power-to-Gas installation of 12 MW in Delfzijl
3 - May 2014 - A consortium investigated a revenue model for a Power-to-Gas installation with a capacity of 5 MW.
4 - Sept 2014 - InnoFasEnergy is conducting a feasibility study into a better and smarter use of energy and the capture and use of CO2
5 - Oct 2014 - Phase 1 Rozenburg (Built Environment) starts
6 - Sept 2015 - Energy Matters, Hanze University of Applied Sciences and partners are developing a reversible fuel cell (RBC) on a laboratory scale.

Store & Go project

In the European STORE & GO project (2016 - 2020), power-to-gas methane production and supply to the gas grid is demonstrated at 3 locations in Europe

7 - Sept 2016 - Power to X Nieuwegein
8 - Jan 2018 - Follow-up Project Power-to-X
9 - Nov 2018 - Phase 2 Rozenburg
10 - Dec 2018 - Archypel
11 - Jan 2019 - Flexnode Plus

Hydrogen Plans in the North Sea

Preliminary development

1 - Sept 2013 - Catrinus Jepma argues for converting oil platforms in the North Sea to electrolysis stations
2 - Feb 2014 - Jepma argues that "Power-to-gas at sea is only profitable in the bigger picture".
3 - Feb 2016 - Jepma investigated the feasibility on the basis of business cases for Engie production platforms in the North Sea.
4 - May 2017 - North Sea Energy program has started
5 - June 2017 - Discussions are held with NGOs about plans in the North Sea
6 - Sept 2017 - Gasunie took part in the energy island consortium (on the Dogger Bank)

Energy-island: North Sea Wind Power Hub

7 - Nov 2017 - The parties expressed their view that it would be useful to develop a testing ground for offshore electrolysis within 2 to 3 years.
8 - May 2018 - The North Sea Energy (NSE) Consortium presented the results of the first year of its research program in Scheveningen.
9 - Aug 2018 - A study published by Energy Delta Institute, showed significant cost savings for green North Sea hydrogen production.
10 - Oct 2018 - NSE 3: Focus on the application of hydrogen for the transport of energy from wind farms in the North Sea and the balancing of the energy system.
11 - Feb 2020 - Concrete plans for the first pilot in the North Sea (before the end of 2020)

Public transport hydrogen buses

1 - Dec 2003 - GVB participated in the CUTE project.
2 - Jan 2012 - GVB does another trial in Amsterdam with two Philias hydrogen buses.
3 - Jan 2012 - In Groningen, Qbuzz purchased 2 Van Hool buses for the EU project High VLO City on behalf of OV-bureau Groningen Drenthe.
4 - Nov 2014 - The Ministry of I&W provided subsidies to 5 regions for 10 fuel cell buses.
5 - Jun 2015 - Team FAST development - formic acid vehicle
6 - Feb 2016 - RET orders two hydrogen buses
7 - Aug 2016 - The Province of Gelderland wants to spend the I&W subsidy on 3 buses from Hymove in Apeldoorn.
8 - Feb 2017 - Qbuzz presented the first hydrogen bus in Groningen and Drenthe
9 - Mei 2017 - Connexxion deploys the 2 refurbished buses that ran in Amsterdam (CUTE) at Eindhoven
10 - Juni 2017 - Phileas hydrogen buses repeat project
11 - Sept 2017 - In South Holland, Connexxion has ordered 4 hydrogen buses from VDL
12 - Feb 2018 - In Rotterdam, 2 new Van Hool hydrogen buses are driving at RET
13 - Juni 2018 - Development Team FAST - stationary fuel cell
14 - Juni 2018 - Two hydrogen buses between Apeldoorn and Arnhem
15 - Dec 2018 - Development Team FAST - continued as start-up DENS
16 - Sept 2019 - Veluwe hydrogen buses fully included in the timetable
17 - Jan 2018 - Verdict: 50 buses will be added in JIVE 2 with FCH JU funding in the coming years.

Hydrogen filling stations

1 - Sept 2014 - An Air Liquide station opened in Rhoon since 2014.
2 - April 201 - Power-to-flex project
3 - Jan 2017 - The Netherlands has several subsidies from the programs Interreg, TEN-T and FCH JU brought in.
4 - Feb 2017 - Project NEFUSTA develops a gas station, that contributes the balancing of the electricity grid
5 - Feb 2017 - An installation by Hygear installed in Arnhem.
6 - Dec 2017 - Introduction of a Dutch standard according to the European standard design
7 - Feb 2018 - Hydrogen filling station opened in Delfzijl
8 - Sept 2018 - The Netherlands can use the TEN-T project BENEFIC grant subsidies to 7 petrol stations in the Netherlands.
9 - Nov 2018 - Third public hydrogen filling station opens in Arnhem
10 - Feb 2019 - Power to Flex: Holthausen is building a small hydrogen filling station that peaks and troughs to meet the energy demand.
11 - March 2019 - Verdict: The number of hydrogen filling stations will be in the Netherlands expanded from 5 to ± 16 in 2020 and 20 in 2022.
12 - Dec 2019 - Plans for stations in (10) different cities

Hydrogen cars

H2Nodes

Evolution of a European hydrogen refueling station network by mobilizing the local demand and value chains

1 - Nov 2014 - Toyota's Mirai add a power-out connection to the Japanese version
2 - April 2015 - Project Car as Power Plant: TU Delft investigates supplying energy from hydrogen with fuel cells.
3 - Maart 2016 - Dutch company Accenda together with Hyundai a fuel cell vehicle fitted with an electrical outlet as an electricity output.
4 - Jan 2017 - Dutch company Accenda in Delft builds cars (Hydroelectric resp. Ekoelectric) (H2Nodes)
5 - Jan 2017 - Municipality of Arnhem wants to attract more cars in the context of the European H2Nodes project.
6 - Dec 2019 - H2Drive: Arnhem stimulates driving with this on hydrogen (especially financial)

H2ME2

Aim to include 200 cars (Hyundai and Mercedes), 125 electric delivery vans fuel cell range extender on the road in Europe

7 - Mei 2016 - the Netherlands participates in H2ME 2 (2016 - 2022)

Figure 4.9: Legend related to the Event Map of all relevant hydrogen events in the Netherlands

4.4 ESA of Hydrogen in the Mobility Regime: For zero-emission traffic and transport

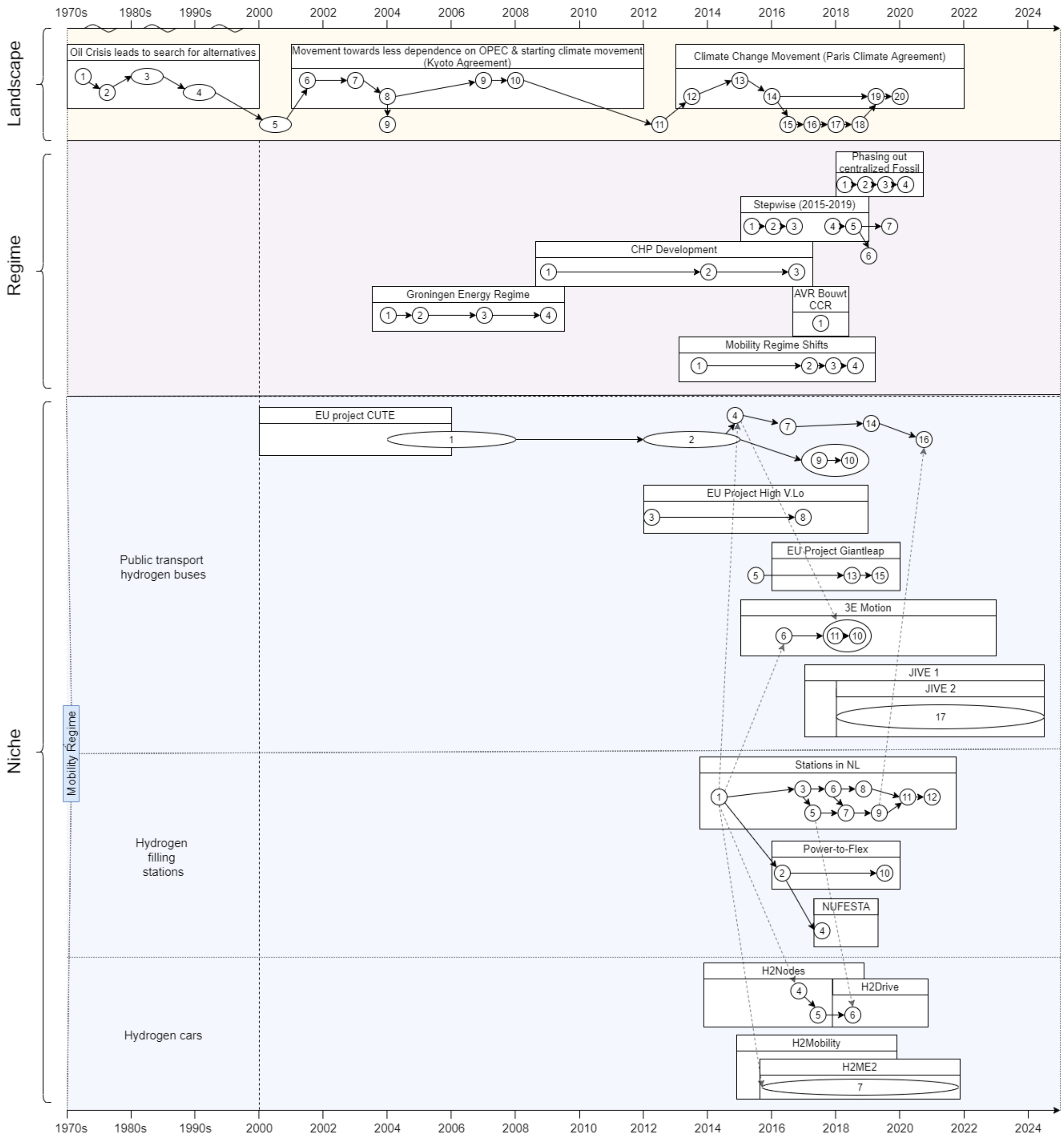

Figure 4.10: Event Map of all relevant events for Mobility applications of Hydrogen

4.4.1 2000 - 2013: Initial Development after the search for independence from OPEC

The September 11, 2001 attack in the US was an immensely impactful Landscape event that set-in motion the increased interest in the potential for hydrogen to play a major role in the world's long-term energy future due to a need for independence from OPEC. This led to the coining of hydrogen as "freedom fuel" by the US president (Wired, 2003) and a redistribution of the majority of the renewable energy fund towards the US hydrogen initiative (made official in 2003), with an explicit priority towards practical applicability of hydrogen in mobility, guided by research on the hydrogen economy by the National Research Council (NRC) (NRC, 2004). This increased attention in the US caused the EU to also gear its focus towards the molecule (European Commission, 2003a, 2003b), leading to the first European hydrogen project in the 2000s, called Clean Urban Transport for Europe (CUTE) in December 2001. This project received one of the largest funds ever from the European Commission (EC) (IEA, 2001) , stemming from their ambition to promote the fuel, through which 9 European countries (incl. Amsterdam) tested hydrogen fuel cell buses between 2003 and 2005 (NRC, 2003; De Volkskrant, 2003). This project, having been the first volume-production test of this scale conducted worldwide, was highly influential for the global and Dutch hydrogen transition.

In the Netherlands, the Amsterdam municipal transport company GVB participated in the CUTE project, with the buses driving 2 years longer than the intended time (from 2003 to 2008) (De Volkskrant, 2008b). The experiment showed the necessity of a tank infrastructure, since GVB had to build its own mini electrolysis factory, which made hydrogen production relatively expensive. Unintendedly, this factory caused protest from surrounding residents due to fear of an explosion of the flammable hydrogen gas. These protests were, nevertheless, subdued due to an analysis by engineering firm Royal Haskoning, which showed that the probability and effect of a potential explosion was negligible. During the experiment, the buses experienced quite some technical difficulties, mainly due to lackluster lifespan of the fuel cells. The buses were also relatively expensive compared to alternatives (battery electric or internal combustion buses); the cost of a fuel cell bus was still ten times more than internal combustion buses (Cockroft & Owen, 2008).

Aside from the technical and financial deficiencies, the buses were a "success story" from the perspective of its users, mainly attributed to their comfort and silence (De Volkskrant, 2008b). Therefore, CUTE's conclusion led to an investment decision of the municipality of Amsterdam into hydrogen research, along with an announcement that it saw hydrogen as a vital fuel due to its sustainability potential (Parool, 2008) ; causing them to start inquiring into experimentation with other modes of transport (such as tracks and canal boats), directly leading to the implementation of a hydrogen-powered canal boat in 2009 (Parool, 2009). GVB also initiated a direct follow-up of the CUTE implementation, starting in 2012, which implemented the learning processes from the preceding experiment, improving most of the technical deficiencies (making them more efficient) (OVPro, 2012). The main barriers that now remained were related to the need of a tank infrastructure and the costs of the vehicles.

SNM Consideration
At the end of the experimentation, general expectations towards the future potential of the energy carrier were positive, while there was a consensus that there was still a necessary "learning curve" before large-scale development would become (profitably) feasible. The learning process in combination with the positive expectations directly led to a network building effort by GVB Hydrogen Bus Alliance' together with public transport companies in London and Hamburg, among others - with the goal of convincing car manufacturers to invest in hydrogen buses.

Due to the technical and financial deficiencies, aside from the highly influential CUTE project, hydrogen developments in the transport sector remained relatively stagnant in the period between 2003 and 2008. A wave movement in social and political interest, resulting in fluctuating subsidy flows – strengthened by the financial crisis of 2008 – led to the cessation of almost all activities related to research and development of hydrogen technology in (semi) public institutions around 2008 (until after 2012). ECN was the clearest example of this, where full research into hydrogen technology was discontinued in 2009 (ECN, 2012).

4.4.2 2013 - 2020: Towards practical implementation after the Climate movement

In the period starting from 2013, it can be seen in Figure 4.10 that mobility events increased exponentially, especially practical experimentation with hydrogen buses. Notable is the observation that most of the experimentation in this period are embedded within European projects, or have been the subject of European funding. This influx can be directly attributed to the increased Landscape pressure that arose from the climate movement, which was kick-started by the signing of the SER accord in the Netherlands. This Landscape pressure almost immediately caused Dutch transport companies to formulate the ambition that by 2025 all public transport buses no longer would emit air-polluting or climate-damaging emissions—both through the use of hydrogen, as well as with hybrid and electrically powered buses (officially agreed upon in 2016) (Ministerie van Infrastructuur en Waterstaat, 2020).

As a consequence of the increased landscape pressures and regime internal tensions, along with the outcome of the CUTE experiment that there was a need for a hydrogen infrastructure, the first public hydrogen filling station was opened by Air Liquide in Rhoon (near the Rotterdam industry cluster) in 2014 (OVPro, 2019). This station was seen by the company and the Dutch government as a first step towards a nationwide network of hydrogen stations (ibid.). When the filling station was built, there were only two Rijkswaterstaat-owned Hyundai hydrogen vehicles that were customers of the station; Hyundai was the first to market hydrogen-powered passenger cars on the Dutch market in 2014 (TaxiPro, 2014), after the company had invested in R&D for fourteen years, making the vehicles very expensive (EUR 140.00) (Hyundai, 2014; GlobeNewsWire, 2018). Because of this, the cars were only available for the business market, with the company expressing that they only wanted to enter the public market after 2017 (Caradvice, 2013). Due to the expense and lack of demand along with the ambitions of Air Liquide with support from the government, there was no period for the location to pay for itself (Air Liquide, 2018, 2014).

The opening was closely followed by the Ministry of Infrastructure and Water (I&W) granting 5 Dutch regions a subsidy as a contribution to their existing plans to make their fleet cleaner and quieter in 2015, with a specific directive to increase the hydrogen bus fleet and hydrogen fueling stations (Ministerie van Infrastructuur en Waterstaat, 2020). Here, as well, the EC stimulated the Dutch government through the draft directive on the deployment of Alternative Fuels Infrastructure, in which they asked member states to develop a hydrogen tank infrastructure (European Commission, 2014). This funding, in addition to the previously mentioned landscape pressures on the regime, facilitated the implementation of multiple buses on Dutch roads (Rotterdam, Arnhem, Groningen) between 2016 and 2020, usually as part of a European project or with additional European funding. These implementations will be discussed in detail in the following subsection with reference to this subsidy. These experiments were pivotal for the hydrogen transition, as they uncovered pivotal (first- and second order) learning processes, which further optimized future implementations.

SNM Consideration

Most notably, from a technical perspective, VDL improved battery technology and a regenerative braking system to improve range (10-20%) and service life. Nevertheless, hydrogen buses were far from being mature products, and thus need new experimentation in real-life situations. The hydrogen bus still cost about four times as much as a diesel bus and twice as much as an electric bus. The fuel was also still relatively expensive, primarily due to the high-pressure (350 – 700 bar) refueling and the decentralized production of hydrogen in small. Even though companies like Hermes and VDL saw more future in electric buses - due to financial considerations - general expectations were still positive for the future of hydrogen, mainly due to the considerably larger range of hydrogen (second-order learning). Therefore, next to investing in electric buses, the company continued R&D towards hydrogen buses (especially with the Phileas-type bus), which were later successfully implemented in practical experimentation.

As uncovered through the implementation of the Rhoon filling station, one of the most significant barriers was the high cost of filling stations. Therefore, for years (until 2017), the number in the Netherlands was limited to three locations (Rhoon, Delfzijl, and Helmond). It was only after interoperability of hydrogen filling stations was ensured in 2017 by the introduction of a Dutch standard, in accordance with the European standard design that a window of opportunity opened in Sep 2018 for the Netherlands to subsidize seven petrol stations via the Ten-T project BENEFIC (Netherlands Enterprise Agency, 2017; TKI Gas, 2017). This opening was facilitated by a Dutch consortium (Turnhout) consisting of WaterstofNet Colruyt Group, PitPoint, Shell, and Rijkswaterstaat joined the "H2Benelux" project, which had the objective of deploying a Benelux network of hydrogen refueling stations (HRS) -, co-financed by the EU's Connecting Europe Facility (CEF) (European Commission, 2017;

Rijkswaterstaat, 2017). In addition, Shell and PitPoint also received subsidies from the Netherlands Enterprise Agency (DKTI Transport) for the construction of the Dutch stations (Pitpoint, 2018a). Because of this, in early 2019, the Netherlands increased to five hydrogen filling stations located in The Hague, Rhoon, Arnhem, Delfzijl, and Helmond.

SNM Consideration
Near the end of 2019, the network of hydrogen stations was also growing in European countries, most importantly for the Dutch hydrogen transition in Denmark, Germany and Belgium. This brought positive expectations for drivers of hydrogen cars in the Dutch-German border region because they would then easily be able to fill up with hydrogen in neighboring countries.

As seen in Figure 4.10, the transition pathway in the mobility sector has mostly been guided by European projects and funding. In the following subsection, these projects are described per European project, even though they have mutually influenced each other as well. Especially between 2015 and 2017, there were many developments within Europe and the Netherlands concerning hydrogen buses for public transport; Around a total of 10 buses had been implemented in different Dutch regions. One key Dutch initiative is described in a separate subsection; even through it has also been influenced by European initiatives, it showcases the necessity of regional initiative and embedding.

4.4.2.1 International Collaboration

3Emotion (2015 – 2023)
Under the 3Emotion (Environmentally friendly Efficient Electric Motion) project (2015 – 2023), which started in 2015 with the intention of bridging the gap between current fuel-cell bus demonstration projects and larger-scale deployment, multiple buses were implemented in the Netherlands (Hydrogen Europe, 2018). Through this project, 6 'van Hool' hydrogen buses were implemented by transport company RET in Rotterdam, which were also partly subsidized by the Dutch government and the Metropolitan Region of Rotterdam The Hague (MRDH), which wanted to use the experience and knowledge that the RET acquired in future concessions (FCH, 2017). Simultaneously, Hermes (subsidiary of Connexxion) had the ambition of implementing two hydrogen buses in the Eindhoven/Helmond Area (OVPro, 2017). This ambition stemmed from the landscape pressure of the Paris Agreement in 2015, which put in place the agreement between carriers and the government to make transport emission-free, along with high expectations for the future of hydrogen in public transport. The Eindhoven area was particularly suitable due to the nearby (private) filling station in Helmond, which had been built in 2013 (WaterstofNet, 2013).

After these buses were successfully implemented and became part of the regular timetable in 2017 without technical difficulties, the same company (VDL)- under 3Emotion with investment from FCH-JU and the Ministry of I&W -, delivered four hydrogen buses to the Connexxion concession 'Hoekse Waard-Goeree-Overflakkee' (HWGO) in 2019 (FME, 2019). The capacity of the Rhoon filling station was increased accordingly, to be able to supply the four buses with hydrogen during the day.

SNM Consideration
Characteristic with these implementations was the fact that both the implementation in Rotterdam and in Eindhoven involved buses that were already previously used in different projects. From these projects, learning processes were implemented in the redesign of the buses from a technical perspective and the implementation could also go more smoothly due to the previous experiment. The buses in Rotterdam were already used in Antwerp, Cologne, and Aberdeen. More notable was the fact that the buses implemented in Eindhoven. were the exact same buses that had previously driven in Amsterdam in the CUTE project, which then suffered from technical deficiencies. These learning processes were used as inputs for refurbishment by bus manufacturer VDL, before deployment in Eindhoven (lateral sharing of information). Finally, the fact that Connexxion had ordered the buses for HWGO, in collaboration with VDL, was important from an SNM perspective, since a Connexxion subsidiary (Hermes) had previously successfully implemented very similar buses in Eindhoven (also converted by VDL from the CUTE project). Due to this, the plethora of learning processes could be taken into account, and it shows, since this implementation went quite smoothly.

Project V.lo (2015 – 2019)
Under the European V.lo project (2015 – 2019), which started in 2012 with the aim of facilitating the deployment of fuel cell buses and hydrogen refueling stations across Europe (Hydrogen Europe, 2012), Groningen transport company Qbuzz started investigating the possibility of hydrogen buses immediately after the Dutch energy agreement was signed in 2013. The company saw the supply of fuel as a significant barrier towards using hydrogen, they launched an investigation in 2014, which focused on inter-sector collaboration with chemical companies to reuse their hydrogen in the mobility sector (OVPro, 2014). This project was once again co-financed by the province of Groningen and the ministry of I&W. The investigation ultimately led to the collaboration between Nouryon (AkzoNobel) and Pitpoint in order to build a publicly accessible filling station in Delfzijl. Due to the positive conclusion of the study (in 2017) and the availability of a filling station, Qbuzz purchased 2 'van Hool' buses as part of the high V.lo project, which were previously used in San Remo, where the buses could not be used properly due to the lack of a filling station (WaterstofNet, 2017; Pitpoint, 2018b; 3Emotion, 2017).

EU-project Giantleap (2016 – 2019)
In 2016, many Fuel-Cell Electric buses had already been implemented in various countries in Europe, Canada, and the USA, but they were still costly with low availability. Oddly enough, the low availability had almost always been due to control issues and hybridization strategies rather than problems in the fuel cells themselves. Because of the EU-project Giantleap (2016 – 2019) (Hydrogen Europe, 2016) VDL had supplied over 200 electric buses, with another 200-300 in the pipeline. In order to bring the cost of a fuel cell system below EUR 100,000, the use of a cheaper fuel cell with a longer service life was seen as essential; The development of this was the aim of the Giantleap, in which VDL participated alongside Bosch (CORDIS, 2016).

JIVE (2017 – 2023)
Under the JIVE 2 project (2018 – 2023) - which together with JIVE 1 (2017 – 2023) is the largest planned deployment in Europe to date (FCH, 2017), planning to deploy nearly 300 fuel cell buses in 22 cities across Europe by the early 2020s – 50 buses were planned in the Netherlands to be distributed across Groningen (20), South Holland (20), and North Brabant (10) (OVPro, 2019). A major bottleneck for these implementations was the lack of filling stations, thus the involved parties within the respective provinces requested filling station expansion accordingly. In the province of Groningen, the existing Delfzijl filling station was requested to be expanded and there was a need for a publicly accessible filling station in the Groningen (Fuel Cells Works, 2019). In the summer of 2019, Shell Netherlands had made a tender, pending the construction of a new hydrogen station in Groningen, among other things, for the planned 20 buses (Shell, 2019). Furthermore, in the South Holland province, a public filling station was planned in 'Oude Tonge op Goeree' (Greenpoint, 2018) and in North Brabant, the construction of an additional filling station (apart from Helmond) was being prepared in Breda (Greenpoint, 2020).

SNM Consideration
Together with the Ministry of Infrastructure and the Environment, the provinces involved have since investigated, together with a particular project organization, to enable joint procurement of the buses and the necessary hydrogen with the lowest possible TCO. This is a first example of a positive sign of good quality network building, in which competing companies are open to working together for the mutual benefit of each company and the hydrogen transition as a whole. Bundling demand in the Netherlands on a larger scale could also change the car industry. Some companies also considered joining forces in 2017 and jointly purchasing fuel cell cars, but no concrete project was underway.

4.4.2.2 Prominent Dutch initiative: Province of Gelderland

In 2015 the Province of Gelderland ordered 4 hydrogen buses in Apeldoorn Ouden, subsidized by the ministry of I&W (OVPro, 2015). Refueling was still a handicap due to the lack of fueling stations; the Hymove buses had to drive up and down to Helmond in the first months (OV Magazine, 2017). Because of this Syntus started with one bus driving two short trips. This led the province to initially rejected a plan for a follow-up in early 2017 (Provincie van Gelderland, 2017). Around the same time in 2017, the municipality of Arnhem also announced that it wanted to attract more hydrogen cars for demand bundling - in the context of the European H2Nodes project – and by contributing with tax benefits that would apply until 2020 (VerkeersNet, 2018) to decrease the costs for users. However, it turned out to be challenging to get more supply, since the central part of the production was reserved for the leading hydrogen markets, where a more extensive refueling infrastructure already existed, and the industry cooperated in consortia (such as H2ME).

SNM Consideration
In 2017, various parties had plans to open more hydrogen locations. Expectations for hydrogen were high for the future of more sustainable road traffic, both in the passenger car and truck segments, even though only a handful of cars and buses were driving in 2017.

Arnhem's interest stemmed from the fact that the municipality saw itself as the 'electricity capital' of the country, with head offices of major energy suppliers and the renowned trolleybuses within the city limits (Duurzaam Gebouwd, 2012). So, when the local pump operator stopped supplying hydrogen just before this announcement, the municipality immediately set up new plans to build a large hydrogen refueling station. This was also because the municipality had hydrogen cars, for which the nearest pump would be in Helmond when the local filling station closed. As a consequence, to fill the gap, Hygear - an Arnhem company specializing in the supply of gases - opened a temporary (heavily subsidized), publicly accessible filling station in Arnhem in Feb 2017 (TankPro, 2017). At this station hydrogen could be refueled at 350 bar (which is optimal for buses), thus there was still a need for a high-pressure filling station of 700 bar (which is optimal for cars). It was only after this station was realized, that the trial with the hydrogen buses by Syntus was extended by the province.

SNM Consideration
Arnhem's hydrogen bus manufacturer 'Hymove' and a small Polish bus supplier 'Solbus' had an agreement to build the first 200 hydrogen buses together to gain some practical experience with a producer with prior experience. Solbus also built the buses that were previously implemented; from previous projects, technical, financial, and infrastructure learning processes were included in the construction of the new buses, which made the buses more efficient, by approximately 10%, and economical, from EUR 1.3 million to EUR 750.000.

The one-off filling station in Arnhem would make way for a high-pressure filling station – in the same city (Arnhem) - under construction by Pitpoint, which opened in 2019 after several months of delay due to technical challenges (Pitpoint, 2018d). This became the third public filling station with the first operational Dutch 700-bar column for hydrogen passenger vehicles to refuel optimally (Pitpoint, 2018c). The station was realized under the H2Nodes project with funding from the Connecting European Facility (CEF) and support from Dutch government. The hydrogen was produced on-site using technology provided by HyGear. Due to the realization of this station, Syntus Gelderland had fully included the two hydrogen buses in the timetable in September 2019, after which the company reported reliable operation from a technical perspective.

SNM Consideration
By performing more experimentation, the bus carrier wanted to gain more knowledge and experience about the bus's behavior in the longer term and its the consumption; Bus drivers had to learn to drive differently, e.g., strategically breaking to recover energy, for which they followed a course. The drivers reacted positively to the new vehicles - even though they had to get used to them - by stating that the new buses made them more aware of their driving behavior.

Finally, in December 2019, Arnhem made another attempt to stimulate hydrogen-powered driving, with the goal of implementing at least ninety new hydrogen cars around Arnhem (De Ingenieur, 2019). Through the H2Drive project, the municipality of Arnhem and the province of Gelderland attempted to break through this impasse by offering financial support to users – since a major bottleneck was the high investment cost (H2Drive, 2020). With this financial support, the only thing expected in return from the pioneers was that they would share their experiences with the community of hydrogen drivers and interested people. Similarly here – as in a lot of previous events and interview statements – the problem, especially in the hydrogen transport sector, was often referred to as a chicken-egg story; because there were still too few hydrogen filling stations, people did not want to invest in hydrogen cars and vice versa, no petrol stations were added, because hardly anyone in the Netherlands had a hydrogen car 177 according to the latest figures at the end of 2019 (Rijksdienst voor Ondernemend Nederland, 2019; H2Platform, 2019).

4.4.3 Analysis of key events and influences of the Mobility Sector's ESA

In the Mobility Sector, as described in the previous sections, the key events described in Figure 4.11 can be found. These events have either highly influenced the transition pathway in the Netherlands, or categorize the state that the transition is in. From these key events, sector-specific barriers can be found and they can further be explained by the theoretical framework proposed in Chapter 2. As described by the ESA, these key niche events have been highly influenced by regime and landscape events.

2000 - 2013
The transition pathway in the Netherlands is characterized by two different phases. The first phase (2000 – 2012) was set-in motion by the 9-11 attacks in the US, which essentially kick-started the entire modern global hydrogen transition. This initial phase put extra emphasis on the transition within mobility due to the historical development of fuel-cell technology. This caused the EU to also become interested in developing hydrogen and devoting large financial capital towards the energy carrier. This quite quickly led to the first European project (CUTE), in which the Netherlands also participated. This project brought with it the necessary learning processes, with the main takeaways being that there was still substantial technological development necessary, the costs were still substantial and the lack of a tanking infrastructure was still inhibiting the implementation. Aside from these deficiencies, the project had positive results from the perspective of the users and caused expectations to rise for the future potential, which made the municipality of Amsterdam increase investments and organize a follow-up for the CUTE project. Nevertheless, this period (2000-2012) ended with a 3-year stop of all hydrogen projects between 2008 and 2012, which arose due to the combination of technical and financial deficiencies and a political and financial wave movement that was nudged by the global economic crisis of 2008.

2013 – 2020
The second period commenced in 2013 due to increased climate action (2013 – 2020), which once again emphasized hydrogen as a high-potential energy carrier. This period sees an exponential increase in mobility projects "in the field", with implementations in the order of around 100-200 cars, now 10 and in a few years 60 public transport buses, dozens of garbage trucks and other trucks, one or more trains, one or more inland vessels, and 4 filling stations. In this period there are clear inferences that result from the ESA: (1) Firstly, it has become quite clear that international collaboration, especially within European projects, has been pivotal and has influenced the transition pathway immensely. Almost all projects were part of European projects, or have been co-funded by the EC. Pivotal was the Dutch subsidy grant in this as well. (2) Secondly, the construction of a national network for hydrogen filling stations is crucial for the breakthrough of hydrogen as an energy carrier for cleaner transport. Throughout the mobility ESA description and as can be seen in Figure 4.10, the construction of hydrogen filling stations has been a bottleneck for the implementation of hydrogen vehicles (especially hydrogen buses); either after the construction of a hydrogen filling station, buses were immediately implemented or experimentation did not go well if there was no hydrogen station nearby, causing he experiment to almost be stopped. A key event in this regard was the implementation of the Dutch standard in 2017, which facilitated the construction of two filling stations, with 5 others still pending for construction.

Conclusion
Finally, for both periods, it can be seen that there is a clear succession of niche experimentation and events, where the outcomes of a precious event guides successive events. Noteworthy is the perpetual implementation of hydrogen buses that were previously implemented in other European or Dutch experimentation, which had been improved with learning processes as inputs. Furthermore, the ESA shows the necessity of the implementation of different modes of transport to uncover system deficiencies and windows of opportunities. So, even though Landscape events have been most influential in guiding the hydrogen transition, especially in its infancy, niche experimentation and the outcome of projects can be seen as the motor that drives the transition forward in the right direction. Therefore, it is pivotal that the barriers and windows of opportunities that are uncovered are taken care of so that experimentation can continue.

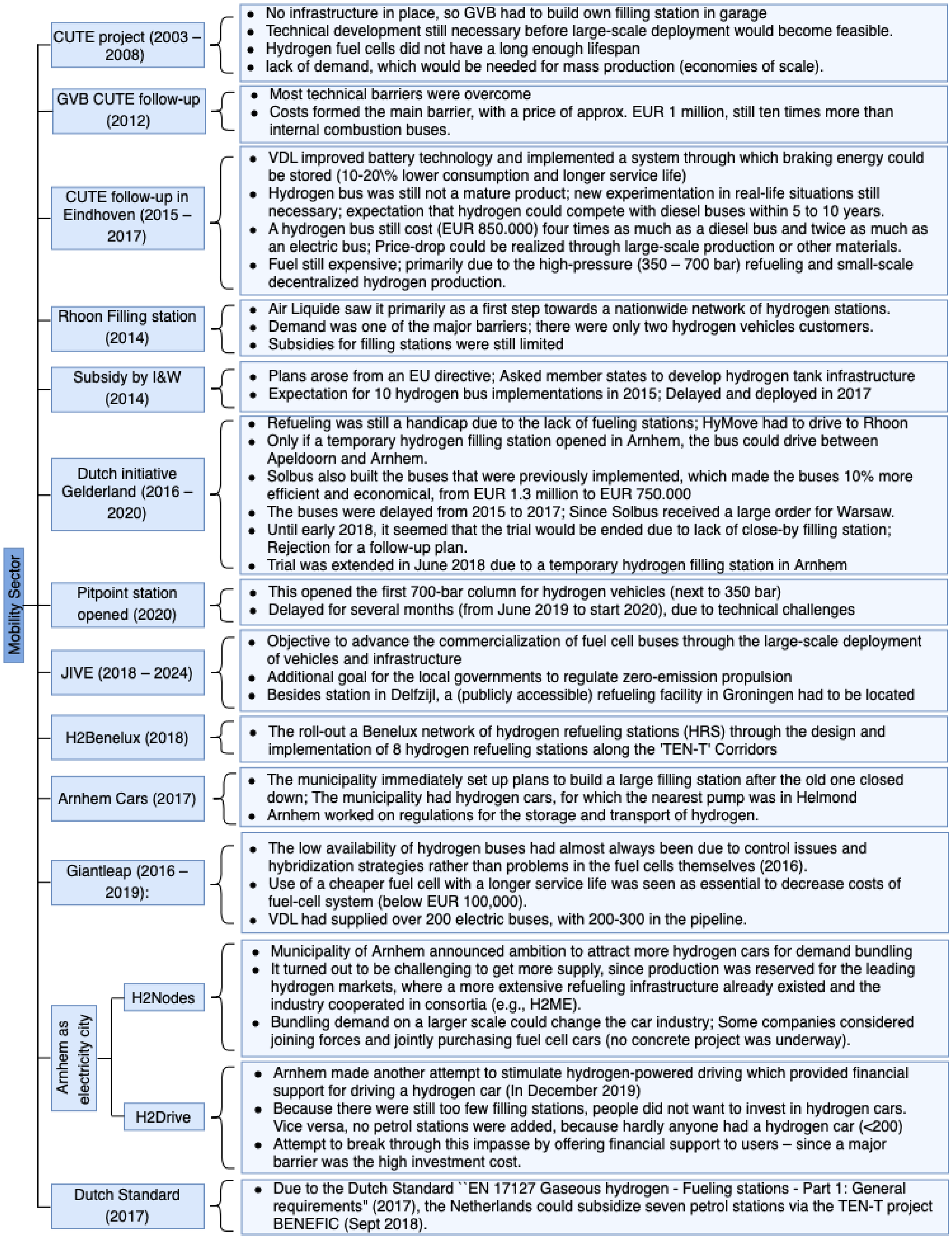

Figure 4.11: Summary of the key niche experimentation outcomes for the mobility developments

4.5 ESA of Hydrogen in the Energy Regime: For system integration, flexibility and energy storage (Gas-to-Power)

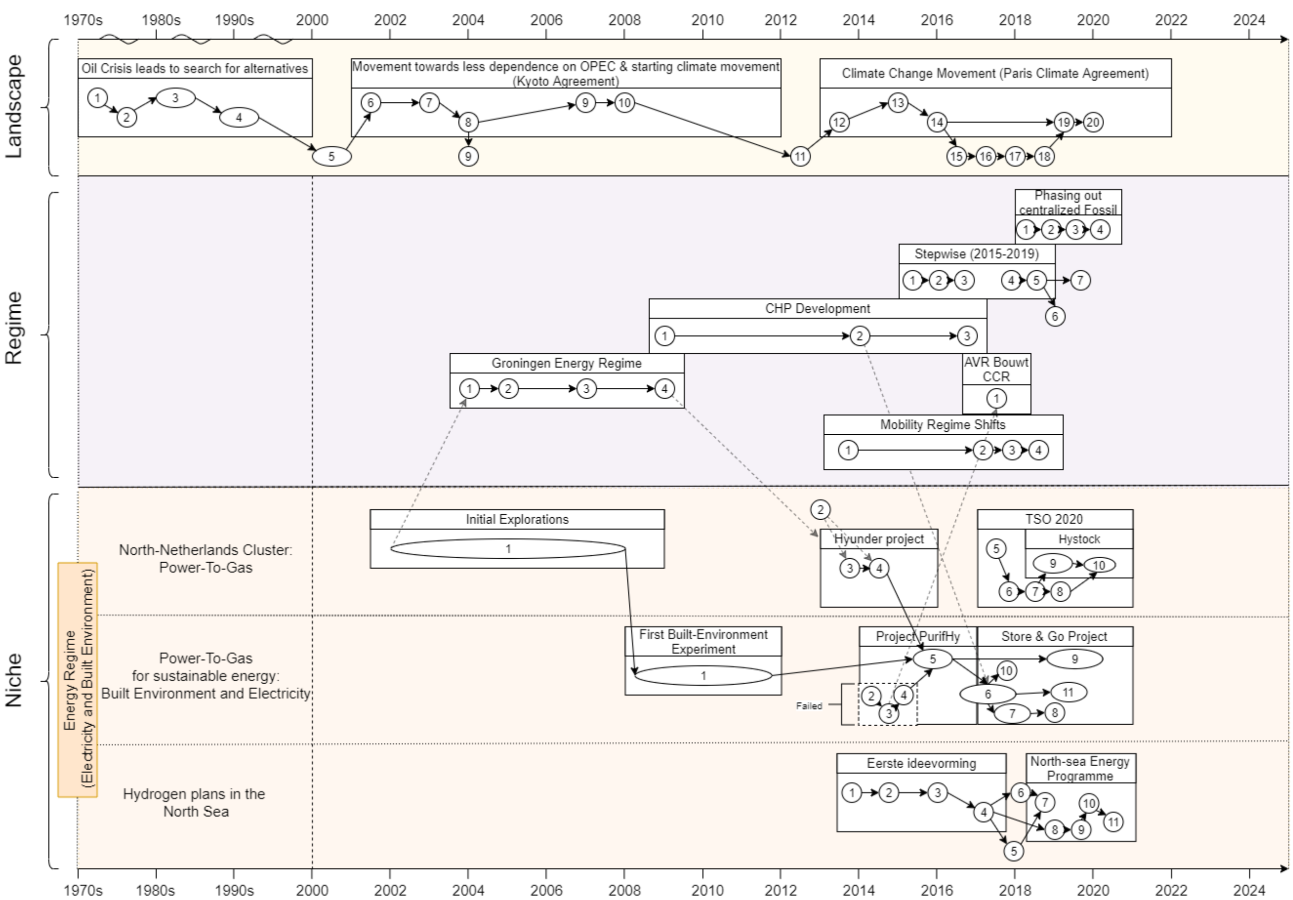

Figure 4.12: Event Map of all relevant events for Energy applications of Hydrogen

4.5.1 2000 - 2013: Initial Development after the search for independence from OPEC

After the 9/11 attacks the US president pumped over $1 billion into the hydrogen economy research (The White House, 2003). The EU did not want to be left behind anymore and had also started investing after having dialogue with the US; after smaller-scale initial developments at the start of the 21^{st} century withing the EU (see section 5.1.1), the Netherlands started a Gasunie-led research, co-funded by the Dutch government and the EU, into the use of hydrogen as a fuel as soon as 2002 that lasted until 2008 (Energeia, 2002). Within this period there was an up-rise of hydrogen being central to many scenarios about the future energy consumption, with a transition period in which natural gas would be mixed with hydrogen. Additionally, there were initial discussions about hydrogen from electrolysis, where the required power would come from renewable energy sources such as solar energy, wind energy, or geo-energy (Trouw, 2003).

SNM Consideration
In the early 2000s, there was some initial voicing of positive expectations for hydrogen in the energy sector, e.g., political Parties such as 'Duurzaam Nederland' speaking out about hydrogen as an energy carrier, with parallel encouragement of renewable energy for environmental reasons (?, ?). Simultaneously in early 2003 the US and Europe began discussions to coordinate research into the potential of hydrogen technology, with the expectation that it would make the West more independent from the oil of the Middle East (The Wallstreet Journal, 2003). Although the two regions wanted to work together, they came from two different expectations, with Europe focusing on renewable fuels, while the US was still focusing on fossil (Rifkin, 2002).

Within this period there were multiple influential regime developments, especially in Northern Netherlands, that were influential on the transition pathway of hydrogen. This started with the expression that the Northern Netherlands (Groningen, Friesland, and Drenthe) wanted to establish itself as a (sustainable) energy city for gas, culminating in the establishment of the "Energy Valley" platform in 2004 (Dagblad van het Noorden, 2004). Within this set-up, partnerships with key actors, such as universities, energy producers, and other companies, were facilitated. Crucial for hydrogen was the pre-existing knowledge in the Northern Netherlands about storage and transport of gaseous energy carriers. This immediately led to increased investment in natural gas pumps in the Northern Netherlands in 2005, which was seen as an ideal transition fuel to a hydrogen and biogas-based transport sector (Dagblad van het Noorden, 2005). The facilitation by Energy Valley and the endorsement of CCS by both the government that preceded, which supplied EUR 80 million subsidy through the Borssele Fund in 2006 (Ministerie van VROM, 2006), and the new government that took office in 2007, led to the signing of an agreement on CO_2 capture in April 2007 in Northern Netherlands, by Nuon, the Ministry of Housing, Spatial Planning and the Environment (Dutch: VROM), and the Province of Groningen (Trouw, 2007; Energeia, 2007).

SNM Consideration
Within this period, expectations were already positive, with the general expectation that hydrogen as a fuel could be widely available in the future. Nevertheless, there seemed to be a consensus that financial and technical limitations still formed significant barriers, with the expectation that a transition to a full hydrogen economy could still take another 40 to 50 years. The main limitation was seen in the fact that hydrogen is an energy carrier that would always have to be produced, which is not an efficient process. Furthermore, there was still little prospect for renewable energy which was expensive, but required for sustainable hydrogen production. Finally, for CO_2 capture to become feasible immense under- and above-ground infrastructural investments would be required, and once it would be made, there would be no turning back. Therefore, these skeptics deemed it essential to consider the pros and cons before such an investment decision would be made (Trouw, 2003).

4.5.2 2013 - 2020: Towards practical implementation after the Climate movement

This period starts off with the signing of the Energy Agreement for sustainable growth (SER Accord) by multiple Dutch parties, intending to make the Netherlands' energy supply more sustainable more quickly (Sociaal-Economische Raad, 2013; PBL, 2013); with a share of 4 percent renewable energy, the Netherlands lagged in Europe in 2013 (CBS, 2013). The global climate movement, with its ambitious goals, led to the broader realization that a mix of different solutions would need to be implemented to maintain grid stability in the European energy system. While various solutions were envisaged - such as grid expansion, demand-side management, and electricity storage - with different approaches across European countries, across all cases, increased demand for energy storage technologies was expected, with hydrogen having high potential to solve this. This realization across Europe brought with it the first large-scale study of hydrogen storage in Europe, called the Hyunder project, in 2013. This project examined the technical implementation and possible risks of storing hydrogen gas, with a focus on the underground storage of hydrogen in salt caverns for large-scale seasonal storage of renewable electricity (Hyunder, 2013).

SNM Consideration
This project served as signaling that hydrogen was being pushed hard in Europe, as it followed a set of ambitious targets by the EU in 2013, which were later reinforced by the Paris Climate Agreement (Landscape and Regime destabilizing pressure).

Soon after the Dutch Climate agreement, European Project Purifhy started, in which it became clear that the Dutch government supported hydrogen's system function (Hydrogen Europe, 2016). This led to an influx of positive expectations followed-up by multiple plans and research between (2014 – 2016). Although these projects were a sign of the government's support and the energy carrier's immense potential, the general conclusion of this first round of studies and experimentation showed that the transition would remain challenging. Firstly, in April 2014 a consortium signed a letter of intent to install a 12MW Power-to-Gas in Delfzijl for greening the chemical industry, which would be the largest of its kind globally (Chemie Magazine, 2014); there were already several Power-to-Gas initiatives in Germany of a (considerably) smaller size (6MW) (PV Magazine, 2013). Nevertheless, due to the sheer scale and expense the project was stalled. Soon after, in May 2014, a different consortium (including car manufacturer Audi, which they already had experience in Germany since 2012) investigated a 5 MW installation in Drenthe, aimed at use in mobility (Energeia, 2014b). This project was, nevertheless, also put on hold due to the government's refusal to equalize the taxation of gas cars with that of hybrid and electric cars, making the e-gas too expensive. Finally, in in September 2014, the InnoFasEnery consortium concluded in a feasibility study initiated by waste processor AVR, that under certain conditions a conclusive business case was possible when using 15-20 buses running on hydrogen from electrolysis, but the project had to be put on-hold in 2015 due to insufficient prospect for hydrogen demand in the short term (until around 2023) (De Gelderlander, 2014).

SNM Consideration
As described, the previously mentioned projects and feasibility studies showed similar motivations and conclusions; While Power-to-Gas was seen as an important long-term solution, the business case (financially) proved too difficult and infeasible for the time being. At that time, the term "storage," often in combination with "excess power," often was mentioned in relation to Power-to-Gas (Energeia, 2007). Yet, the same reservations still existed, as between 2000 – 2013, concerning the conversion losses (about 60%).

As a consequence of these (negative) results towards Power-to-gas, which indicated technical and above all economic barriers, it became clear that larger scale investigation was necessary. This led to the European STORE&GO project (2016 - 2020), which focused on integrating Power-to-Gas technology into European energy grids to investigate how mature the technology is (European Commission, 2016). In the project Power-to-Gas methane production and supply to the gas grid was demonstrated in 3 locations in Germany, Switzerland, and Italy to overcome the aforementioned technical, economic, social and legal barriers on a larger (European) scale. The Netherlands was still a front-runner in Europe in this respect since no other demonstrations of Power-to-Gas (methane) had yet been launched apart from the Rozenburg project.

4.5.2.1 Power-to-Gas as System function: Necessary technical development (2015 – 2020)

After the initial phase of studies and projects which were deemed unsuccessful, the learning processes were used as inputs in several experimentations, which improved upon the technology and increased the prospect for hydrogen (fuel-cell) technology. The first of such projects was the the "Flexnode" project (Sep 2015 – Sep 2017), in which a reversible fuel cell (RBC) was developed, that could complete the entire electrolysis-to-hydrogen-to-electricity cycle, due to the uncovering of the need for flexible and integrative solutions that could cost-effectively respond to diverse customer needs as a response to the impact of increased renewables on end-users, energy companies, and grid operators (Topsector Energie, 2018). From a technological perspective, this was a big leap forward since the various subsystems were now integrated into one system. A follow-up, "Flexnode Plus" (Jan 2019 – Dec 2019), further improved on the efficiency of the system (Hanze university of Applied Science, 2019).

SNM Consideration
The Flexnode project used a micro-CHP from Viessman for comparison. Micro-CHP was a parallel-niche development that positively reinforced hydrogen implementation into the incumbent regime. Suppliers Panasonic and Aisin Seiki had entered the European market in 2014 – with Germany becoming Panasonic's first overseas market through a partnership with Viessmann (Panasonic, 2013). This opened the opportunity for Flexnode to become the first to import the technology in the Netherlands. In Japan, Panasonic accounted for half of the roughly 200,000 micro-CHPs with the natural gas reformer and fuel cell installed there since 2009 (Cogen Europe, 2009). The company also aimed to sell "tens of thousands of units in Europe by 2020," (Panasonic, 2017).

A second of such projects was the power to X project in Nieuwegein, which was set up in September 2016, which arose due to the fact that reliability and affordability were seen as the most significant barriers for Power-to-Gas. The project investigated how hydrogen production and heat supply could optimize the use of renewable energy without increasing the electricity grid, by using a solar farm to extracting, purifying and transporting river water to Amsterdam (Water Research Institute, 2016). The results were successful, resulting in an integrated system design which was applicable for the situation in Nieuwegein as well as generalizable to different scenarios through a developed simulation model for the integration of techniques and applications. Next to legislative barriers that did not allow the storage of excessive heat in the soil still needed to be mended, there weren't many technical challenges. The success led to Pitpoint expressing interest in purchasing hydrogen from this project for a filling station in 2017, which they ultimately built and started purchasing hydrogen in Dec 2019 (Pitpoint, 2018c).

A third project, project Archypel (2016 – 2019) developed the technology for a system in which a house could generate all energy on-site and store it as hydrogen and in batteries resulting in a 100% sustainable energy-autonomous house without grid connections (European Commission, 2016). The feasibility study that accompanied this project showed that an Archypel system was technically possible. However, the business case was not attractive at the time, due to the large space requirements of wind turbines or solar panels and hydrogen storage tank and the costs were still too high (Archypel, 2019)).

All of this technical development within this period, which showed technical feasibility, led to a 2020 study by Tennet & Gasunie that showed that an important role was attributed to hydrogen in Europe in the period after 2030, for which an EU-wide hydrogen network would have to be developed (Gasunie & Tennet, 2020). The most efficient way to do this would be to use the existing gas transport network, which the two parties considered necessary to the electricity network, attributing a pivotal role to Power-to-Gas technology in the period 2030-2050 (Gasunie & Tennet, 2019). This study built upon a previous joint vision document that concluded that the primary production of energy in the future would mainly be electric, while sustainable gases as an energy carrier would continue to play a role in seasonal storage and final consumption in sectors that were difficult to electrify. Therefore, the existing transport networks for electricity and gas would have to be linked together in a future energy system by building Power-to-Gas installations.

4.5.2.2 Power-to-Gas as System function: North-Netherlands Cluster Developments (2013 - 2020)

The SER accord was a landscape event that caused regime destabilizing pressure regarding the future of natural gas, which was especially threatening for the economy of the North Netherlands due to the threat to the 'Gaskraan' in Groningen (BinnenlandsBestuur.nl, 2014). This Regime destabilizing pressure combined with increasingly positive expectations concerning the hydrogen niche led a think tank consisting of five prominant scientists to argue for a new economic basis for the province in 2013, based on hydrogen (Groninger Bodem Beweging, 2020). Further backing of their report came in the form of a publication by Energy Valley in collaboration with Royal Haskoning DHV, which pushed for the realization of small-scale pilot electrolysers (1 to 5MW) in Northern Netherlands in the period up to 2020 (Royal Haskoning DHV, 2014). This was a scale that would be suitable for gaining practical experience in realistic conditions, which was still financially manageable. In response, the province of Groningen officially reconsidered the possibilities of hydrogen, which became public in March 2014, when they entered into talks with Audi about the possibilities for Power-to-Gas in the province (RTV Noord, 2014). The province itself found the Eemshaven in particular very suitable as a roll-out area for a Power-to-Gas chain due to the presence of large energy producers, a solid chemical cluster and an extensive natural gas network (Energeia, 2014c).

SNM Consideration

From an SNM perspective it is important to note that Audi already had an installation in Werlte, Germany, where electricity was converted into methane gas. Furthermore, it was then emphasized (in 2014) that it would be a matter of years before anything could be built. From an SNM perspective, this was yet another example that expectations were overwhelmingly positive for the future, but that it was still too early to start developing – the same as in 2003. These expectations were now shared by more actors (Robustness), and they were now backed by multiple instances of research (evidence), described above, which made them of higher quality. Lastly, these expectations made the search more focused and gave guidance to future research, leading for example to the research done by Royal Haskoning DHV, which had conclusions that aligned with the general expectations. As described in the next section, these expectations do not come out of the blue, but are backed by extensive evidence, mainly by a European study through the Hyunder project and Dutch researches by TNO, CE Delft and consulting/research firms such as Royal Haskoning DHV and Berenschot.

A simultaneous development that had a significant impact on cluster formation around the (industrial) harbors was a study of the role that Dutch ports could play in the implementation of the energy agreement (June

2014), which led to the signing of a 'work program' to strengthen the ports' competitive position by five Dutch ports (including those in Rotterdam and Groningen) (Port of Moerdijk, 2014). It set the priorities for the ports until the end of 2016 by identifying six themes, including sustainability and innovation. Some ports (e.g., Ijmuiden, Zeeland, and Groningen) could jointly facilitate offshore wind. As a result, the ports also worked on a study into the application of smart grids and how new energy carriers such as hydrogen could be promoted. In accordance with this, a platform was established for creative solutions for the implementation of the circular economy.

In the next subsection, multiple parallel developments are described, all of which contributed to the eventual construction of the first hydrogen electrolyzer in the Netherlands.

Towards Power-to-Gas hydrogen implementation (2016 – 2020)

A pivotal regime event for the establishment of the first electrolyzer was the fact that Gasunie took a new direction with its gas storage facility in Zuidwending, as a response to the Regime destabilizing pressure, which increased demand for flexibility trading in gas (Energeia, 2014a). This forced Gasunie to offer new services and products to serve gas traders better. To profile itself in the marketplace, the name Zuidwending was erased, and the storage facility continued as 'Energystock' in May 2014, with the goal of capitalizing on the growing need for flexibility in the future due to the increasing share of renewable energy sources in the energy mix of the following years (Energystock, 2014).

Furthermore, in June 2014, the highly influential European Hyunder project published their final publication (Hyunder, 2014). For the European context, the study showed that there was an opportunity to leverage synergies between hydrogen as a storage medium and as a potentially 'green' fuel (e.g., from shared infrastructures), which would enable the extensive deployment of intermittent renewables for applications other than typical electricity applications, most notably for mobility and industry (Focus on all relevant sectors). For the Netherlands specifically, this study showed that in several places in the North and East of the Netherlands there were suitable salt layers with (space for) salt caverns and the right infrastructure in the vicinity - such as the salt industry, water, gas pipelines, and high-voltage grid (ibid.).

> **SNM Consideration**
> As a result of the positive outcome, there was a rapidly growing interest in the role electrolytically produced hydrogen could play for the system integration of intermittent renewables, with a focus on the medium as "universal energy vector," i.e., its versatility regarding a range of end-use applications, which emphasized the implementation on different levels of aggregation.

These positive conclusions, specifically for the potential of hydrogen storage in the Northern Netherlands led to the EU approving their most substantial "Action" (highest hydrogen subsidy ever) for a project in Eemshaven to help make the Netherlands a European 'Hydrogen Hub'. This became European project TSO 2020 (Feb 2017), which was a collaboration with Germany and Denmark to promote investment in trans-European networks in transport, energy, and telecommunications (TSO 2020, 2017), which would contribute to the interconnection between the countries through the COBRA cable to transport renewable energy from Denmark to Eemshaven and then to the Zuidwending gas storage facility of Energystock.

Because of this substantial fund, Energystock and Gasunie New Energy - both subsidiaries of Gasunie – expressed an interest (April 2017) in building the first hydrogen Power-to-Gas installation at Zuidwending, with a capacity of 1 MW with renewable energy coming from a solar farm that would be built on-location. Even though the hydrogen produced would initially be stored in portable cylinders, given future prospects, this was a particularly suitable location since (1) there was direct access to 10 former salt caverns for storage that Energystock was licensed for – of which only five were in use at the time-, (2) the national gas transport network of Gasunie Transport Services and (3) the national high-voltage network (380 kV) of Tennet (learned through Hyunder). Additionally, Energystock already had the necessary knowledge about gas storage, and there was a high potential of future renewable energy supply, particularly with the planned Cobra cable (see project TSO 2020). At the time, the only uncertainty were the subsidies that had been applied for: SDE+ subsidy for the 1.4 MW of solar panels for its energy consumption, and a European CEF subsidy for the 1 MW Power-to-Gas part).

> **SNM Consideration**
> This Electrolyser would (next to gaining experience) be an attempt to create supply with the expectation that demand would follow accordingly to combat the infamous chicken-egg problem (mentioned by multiple actors across different sectors).

In June 2017, Gasunie officially continued the development of a Power-to-Gas installation near Zuidwending in Groningen, called HyStock (Gasunie, 2017). The initiative became part of a larger project led by the Ministry of Infrastructure and the Environment with the aim to research synergies between electricity storage and alternative transport fuels. In addition to Gasunie, Tennet, filling station operator Green Planet, TU Delft, and Energy Valley were also involved in this project, with subsidy from the EC. At the same time, Energystock investigated the extent to which the salt caverns at that location could be made suitable for the large-scale storage of hydrogen so that a supported design would be laid out (Energystock, 2017).

SNM Consideration
This experimentation led to necessary first-order learning concerning Hydrogen injection in the grid, since there was no standardized percentage for the entire country at the time. The findings showed that injection up to 0.5% into the Dutch underground gas storages was feasible for caverns and porous reservoirs, except for the technical integrity of steel alloys. The researchers annotated that more specific investigations were necessary to make sure integrity losses or damage caused by hydrogen did not occur.

Hystock's construction began in November 2018, and was opened in June 2019, officially making it the first Power-to-Gas facility in the Netherlands (with a capacity of 1 MW) (Energystock, 2019; New Mobility News, 2019). As planned, a solar park was simultaneously installed on the EnergyStock site, of which the majority of the sustainable energy (88%), would be delivered to the HyStock project via TenneT's high-voltage electricity grid, enabling energy conversion between the high voltage electricity network and the gas transmission network. The storage cylinders were, as planned, mobile with the capability of being transported to end-users (e.g., transport and industry). The hydrogen would be transported by tube trailers to the Green Planet petrol station in Pesse as part of the TSO2020 project. This was the culmination of all experiments and projects that came before this.

SNM Consideration
Due to its location, the project had great symbolic value (and great future impact on the hydrogen transition) because it brought Tennet (Power) and Gasunie (Gas) closer together when it comes to interaction between electrons and molecules through the energy carrier hydrogen (Good quality Network Building). At the wind-meets-gas meeting in Groningen where the project was sealed, it was also announced that Gasunie would participate in the energy island Doggersbank project. Therefore, this is a pivotal instance of network building from an SNM perspective

At the opening of Hystock in June 2019, despite its relatively small installation of 'only' 1.1 MW - King Willem-Alexander accepted Gasunie's invitation for the inauguration, partly on the advice of the cabinet (Gasunie, 2019). Even though larger plants were already planned - including a 20MW installation in Delfzijl (Gasunie and Nouryon) and there were talks about the construction of a 100 MW electrolyzer (Gasunie and Engie -, Hystock was a necessary first step for the development of a hydrogen economy; It was the first time that the entire chain had been brought together. Furthermore, the larger plants were planned to initially consist of several small electrolysers, such as those here at HyStock. Finally, Tennet could also gain experience with balancing in this way.

SNM Consideration
This signaled positive expectations for the niche and showed that the government attributed an essential role to hydrogen in the energy transition. Parties have also expressed to have interpreted this event as such signaling. Yet, even though the arrival of the king underlined that politics attached importance to the development of hydrogen, parties expressed that in order to realize all the ambitions more was needed from the government than just moral support.

4.5.2.3 Power-to-Gas as System function: North-Sea Developments (2013 - 2020)

In line with the SER agreement, the Top consortia for Knowledge and Innovation (Dutch: Topconsortia voor Kennis en Innovatie (TKI)) had funded some fifty research projects in 2013, within the (green) gas sector, with the expectation that the most critical starting point was to ensure the role of gas on the way to sustainable energy supply in the future (Energeia, 2013). At that time, parties saw two possible practical routes for this: (1) The installation of Power-to-Gas in the system so that surpluses can be put away (the so-called 'peak shaving'), alternatively (2) immediately convert the electricity into hydrogen and then methane gas, for example, at large offshore wind farms. The latter was seen as a good solution, as it may have been cheaper than investing in the grid. Even though offshore investment would remain necessary, the transport was expected to become cheaper and more flexible (trouw, 2013).

SNM Consideration
Development with Power-to-Gas had been very sudden, with it not having been considered seriously five years prior. In 2013, the role of Power-to-Gas was seen as necessary in the system function pillar, even though the market was still in a very early stage, with little demand. The main concern was that making money with Power-to-Gas was still a long way off.

After some initial voicing of expectations in 2013 the Energy Delta Institute (EDI) advocated the use of superfluous offshore oil and gas platforms as green hydrogen factories in early 2016. This came after research conducted by EDI – on behalf of the Ministry of Economic Affairs - into the feasibility and business case of Engie's production platforms in the North Sea, with the conclusion that sustainable hydrogen on offshore gas platforms could be affordable within the 'foreseeable' future (FluxEnergy.nl, 2016). The study showed that gas platforms near these far-off wind farms could save decommissioning and cabling costs by producing hydrogen directly at sea. Therefore, the depreciation of the drilling platforms was important for the business case, which faced high decommissioning costs. Furthermore, the costs and cable losses for bringing wind power ashore also increase as developers build wind farms further at sea.

SNM Consideration
Due to the results the parties were hopeful that a pilot project could start before 2020, expressing a strong drive for action in the sector. Furthermore, they expected excellent market opportunities for this green hydrogen, assuming that it would be approximately twice as valuable as grey hydrogen.

Towards Practical experimentation on the North-Sea (2017 – 2020)
As a direct result of the previous research by EDI, the North Sea Energy (NSE) program, with a research group led by EDI, executed by some 20 parties from the offshore industry - started in May 2017 intending to bundle activities related to energy extraction around the North Sea in order to help accelerate the energy transition (NSE, 2017a, 2020b). The first studies focused on the added value of platform electrification, with power from wind energy as opposed to gas, as the first step of system integration. The results of these studies, supplemented with Carbon Capture Storage (CCS), were tested in two demonstration locations (IJmuiden Ver and 'Hollandse Kust') in a follow-up study (NSE, 2017b). In May 2018, the first results showed that in the foreseeable future green hydrogen could be produced at a cost similar to that of grey hydrogen at the time, which would be lower than most estimates for converting electricity into hydrogen onshore due to savings of the power grid, while using the existing offshore gas infrastructure (NSE, 2018; TNO, 2018). Smart system connections between offshore gas and wind production also offered opportunities to contribute to the Paris climate goals.

SNM Consideration
The program also indicated an ambition to limit societal and environmental costs, which led them to engage with NGOs, which cautiously reacted positively after initial resistance to disturbance of marine life. Fishermen's interests could still lead to resistance. Because of this, the NSE expressed that governments around the North Sea would have to stand behind the plans, after which the TSOs of the other countries would also follow. At that point in 2018, according to the involved parties, the conversion of electricity into hydrogen was expected to become increasingly important, given the increasing proportion of the electricity supply that had no storage. Furthermore, the power grid was sometimes unable to cope with an abundant supply of electricity and, making it was necessary to convert surpluses of electricity into an energy form that was easy to store, transport, and use.

After these positive results and several parallel developments - most particularly Tennet also advocating the role of hydrogen in the North Sea in October 2017 (Energeia, 2017a) and TNO (participant of the NSE program) concluding that there were still many obstacles to the combination of wind, hydrogen and existing gas pipelines in the North Sea (TNO, 2018) – Because of these observations, the Dutch government was advised by the EU to spend 200 million euros per year on experiments with the business community to convert electricity into gases. These regime destabilizing pressures in addition to the observation that after 2035, all near-shore windfarm possibilities would be used (an additional 10-14 GW), and one would have to go further out to sea, TenneT TSO BV, TenneT TSO GmbH (Germany) and Energinet.dk (Danish TSO for both electricity and gas) initiated the energy island consortium - supported by the European Commission - that wanted to link all wind farms in the North Sea via an artificial island on the Dogger Bank.

In September 2017, Gasunie announced that it would join the consortium, explicitly investigating the possibilities of converting part of the wind energy on the island into green hydrogen, with the ambition to bring ashore as much as possible via existing gas pipelines (to reduce infrastructural investments). This collaboration was made possible partly because Gasunie and TenneT had conducted their first collaboration for the 1MW Hystock plant in the Northern-Netherlands

> **SNM Consideration**
> As a result of the significant plans for wind energy in the Netherlands, several parties considered it useful - at the end of 2017 - to develop a testing ground for offshore electrolysis within 2 to 3 years. This would have to be done in preparation for large-scale hydrogen production from wind energy at sea, in order to gain experience with e.g., the generation of wind hydrogen under North Sea conditions, with transport from hydrogen to shore - by admixing in a natural gas pipeline or by dedicated pipelines -, and with regulations and procedures. Actors expressed that it had to become an (open) testing ground where multiple suppliers could test their systems. *This showed the need for a testing phase, with the initial ideation regarding an Energy Island (Nov 2017).*

As a follow-up, at the end of 2018, the third NSE study program (NSE 3) started, which mainly focused on the use of hydrogen for transporting energy from wind farms and balancing of the energy system (new Energy Coalition, 2018). The results of the study – by building on various existing studies incl NSE 1 and NSE 2 - were intended to support the development of a robust energy policy of the Dutch government regarding the North Sea as a sustainable energy source for the period 2023-2030 in order for the government not to opt for sub-optimal partial solutions (TNO, 2018). An optimal solution would involve looking at different systems and collaborating with other North Sea countries, coastal provinces, ports, and industrial clusters. In this way, the aim was to develop the North SEA optimally as an important energy transition area.

> **SNM Consideration**
> Parties now saw blue hydrogen as an important interim solution for heat supply and gas power stations, with future potential for green hydrogen. This realization can be attributed mainly to studies showing that there would not be enough surplus renewable energy until at least 2030, even though the Paris agreement exerted pressure on the Netherlands to limit CO_2 - with coal-fired power stations closing down and natural gas extraction being reversed. According to the parties, empty gas fields in the North Sea were the logical candidate for storing CO_2.

Quickly after, in early 2019, NSE announced the deployment of a sea container containing a hydrogen factory on an old oil or gas platform (called hydrolyzer) at the end of 2019 with a capacity of 1MW, funded by the Ministry of Economic Affairs and Climate (Technisch Weekblad, 2019). This test has postponed to 2020, which would still make it the first hydrogen factory at sea worldwide, and collaboration has been sought out with Neptune Energy. The set-up would be placed on one of their Energy oil and gas platforms 13 km off the coast of The Hague and is intended to see how the hydrolyzer behaves at sea, which technique would be best suited and on which platform it would be placed.

> **SNM Consideration**
> The future expectation was that it would be the start of a high-speed renovation of the North Sea, whereby hydrogen production would be scaled up quickly. This was in line with the expectation that more wind farms would be built in the North Sea, whereby the capacity of those mills would have increased from one gigawatt to 12 gigawatts; even at 1 GW, Tennet was not able to cope with the influx of electricity. Calculations showed that it would only worsen until 2030 if Tennet did not invest, on a large scale, in the construction of high-voltage power lines. This could potentially be circumvented with hydrogen at sea, which would be much cheaper (approximately ten times cheaper) than bringing the electricity to land and using it to make hydrogen.

Finally, in June 2020, the NSE program concluded that the Netherlands could save billions of euros by not only generating electricity in the North Sea with windmills, but also 'new gas' in the form of hydrogen (NSE, 2020a). This would be due to the system benefits (storage and transport) of hydrogen, as described in Chapter 2. The report especially pointed out that decisions had to be made to get the infrastructure in order. The Netherlands was not the only country that wanted to bet on hydrogen. Mid-2020, the Dutch government called for a greater focus on hydrogen in the EU - including Germany, France, Belgium, Luxembourg, Austria, and Switzerland (NOS, 2020). Germany decided shortly afterward to invest nine billion euros in the development of hydrogen production.

> **SNM Consideration**
> As seen in previous events, both companies and governments were increasingly advocating hydrogen as a new climate-friendly solution for energy issues. The TNO report was important for the discussion then going on about the future energy infrastructure in the Netherlands at sea and on land; The future of hydrogen would help determine the relationship between cables and pipelines in the Netherlands.

4.5.2.4 Power-to-Gas for the Built Environment

2000 - 2013: Initial Development after the search for independence from OPEC
The first event in the built environment came in 2001, when a demonstration project, led by Energyned in collaboration with Eneco, Essent and Nuon with the so-called 'SOFC fuel cell' that started in 1998 in Duiven, was completed with positive results, showing that the fuel cell was able to function in a normal operating situation (EnergyNed, 2001). Even though the fuel cell was running on natural gas, the initiators saw a high potential for hydrogen use with the so-called power plants of the future (Essent, 2002). As a result of this 'success story,' Essent Energy continued experimentation at the end of 2002 with tests of the fuel cells in a house, with results showing that hydrogen showed better performance than natural gas (ibid.).

After this initial development, a four-year study commenced in 2008 by Gasterra and Eneco subsidiaries, Joulz and Stedin at Ameland (2008 – 2012) into the effects of mixing hydrogen produced from solar energy in natural gas (Stedin, 2012). This was the first test of this scale (in Europe), where fourteen homes in an apartment complex were supplied with natural gas injected up to 20% with green hydrogen. The results of this first practical test were quite positive from a technical perspective, with the conclusion that sustainably produced hydrogen can be added to the natural gas network without any problems (ibid.) and the long- term admixture of hydrogen had "no demonstrable influence" on various piping materials and gas appliances (Kiwa, 2012). However, it was mentioned that the efficiency of the conversion process (of 50%) still had to be improved (Stedin, 2012). From a socio-technical perspective the residents also experienced no difficulties and did not notice a difference in use.

SNM Consideration
Due to these findings, project partners were very positive from both a technical and societal perspective, and they had high expectations for the future, calling it promising, advocating further research and application in larger pilot projects. Therefore, the natural gas network appeared to be an interesting storage place for surplus sustainable energy. The project partners and researchers did recommend an upscaling of the Ameland trial, advocating that the longer-term effects (longer than four years) should be examined more closely, as well as the impact on other installations (for example in the industry) and older gas appliances. They also expected that the application of so-called high-temperature electrolysis (HTE) in the future would increase the process efficiency to 75%, making it attractive.

2013 - 2020: Phase after the climate movement
After the developments in Ameland, the European project PurifHy was initiated in 2013, which included project partners ECN and Stedin (European Commission, 2013)). They investigated the possibility of selectively removing hydrogen from the sustainable gas flow to inject it into the existing gas network with inputs from the previous project in Ameland; the project showed that here were barriers to hydrogen utilization within the gas system due to limits on the gas composition. Due to this, HyET ultimately developed a new technology in 2014 which made it possible to selectively pump hydrogen into or out of a gas stream, against any pressure difference. In this way, the purification could respond directly to the varying composition of the sustainably produced gas. It was expected that upon successful completion of this project, the purification technology would be approved to be used to condition 'green' gas, with the first demonstration being the integration with the Power-to-Gas project on-site in Rozenburg (PurifHy, 2013).

In line with HyET's planning, the first phase of the demonstration project in Rozenburg started at the end of 2014. In this demonstration project (2014 - 2018), Stedin, DNV GL, the Municipality of Rotterdam, and Ressort Wonen examined the applicability of Power-to-Gas technology in the built environment, with an emphasis on converting hydrogen to synthetic natural gas (by mixing it with CO_2) used for heating in a nearby apartment complex (Stedin, 2014). For this, Stedin opened a Power-to-Gas factory in Rozenburg directly connected with the apartment complex where the tests took place. The demonstration showed that it was possible to use Power-to-Gas to utilize peaks of sustainably generated electricity, with expected future efficiencies of 75% for the electrolyzer and 90% for methanation (Stedin, 2018). While the synthetic natural gas applied with Dutch regulations, the study showed that the yield could increase if a higher percentage of hydrogen were allowed in the methane in the Dutch gas Network (government role) (ibid.). The conversion turned out to be safe and reliable, and the end-users of the gas, the tenants of the housing corporation, were not bothered (ibid.).

SNM Consideration
Stedin opened a Power-to-Gas factory despite the negative expectations towards such factories at the time. E.g., in the same week, ECN released a study that concluded that Power-to-Gas would only be allocated a positive business case after 2030 in the Netherlands - depending on local conditions – due to significant energy losses and substantial capital-intensive investments concerning the small number of operating hours that the installations would make. The study explicitly stated that there was more potential in Ameland's power-to-hydrogen than in the power-to-methane of Rozenburg. Only when the maximum permitted amount of hydrogen gas would be injected into the natural gas network opportunities could arise to methanate the hydrogen gas using CO_2. Stedin's reasoning for investing was based on positive expectations for the future – through 'success stories' - and purely to gain learning processes.

After a successful trial in Phase 1 using electricity that was converted into synthetic natural gas, a follow-up came in November 2018, converting electricity into hydrogen. This made Stedin the first party in the Netherlands to use this technique in a test. In the 2nd phase (2018-2023), the use of locally produced 100% hydrogen for heating was demonstrated – by installing two hydrogen boilers – in an existing apartment complex in Rozenburg (Energeia, 2018). The hydrogen would be transported via a separate Stedin gas network consisting of the same materials as in the regular natural gas network. As opposed to the 'success story' in Ameland and Rozenburg phase 1, mixing was no longer necessary because methanation - a completely CO_2-neutral process - produced gas of natural gas quality.

SNM Consideration
The project owners expressed high expectations for Power- to-Gas, due to its use for preventing peaks in the electricity grid, because of the influx of renewable energy. At the time of launch (2018), there was still little experience with large-scale production, distribution, and hydrogen use. Grid operators, therefore, advocated focusing on industry and a few pilots until 2030. These expectations were in line with that of the Fraunhofer Institute (the German counterpart of TNO), which researched how Power-to-Gas could play a role in the energy transition for years (Fraunhofer Institute, 2014) in a country that was at the forefront of fuel cells and hydrogen technology. They concluded that Power-to-Gas technology's system role was expected to be indispensable in Germany to achieve the renewable energy target of 80 percent by 2050.

Shortly after the start of Rozenburg Phase 2, a new emphasis was put on the transition that the built environment still had to undergo considering the ambitious goals that came forth in response to the Paris Climate Agreement. This will be discussed in the following subsection

More spotlight towards the built-environment transition (2018 - 2020)
In December 2018, a new package of measures was put together by the Dutch government - which built upon the previous draft agreement – that emphasized a transition that would be achieved while minimizing costs for residents by promoting energy savings through increased sustainability (Housing costs Neutrality) (Rijksoverheid, 2018). The cabinet's ultimate goal was to have all 7 million homes and 1 million commercial properties in the Netherlands free of natural gas by 2050. By 2021, all municipalities would need to produce a neighborhood-oriented vision for the transition to sustainable heating. In the negotiators' view, sustainable heating would consist of 50% heat networks, 25% hybrid heat pumps, and 25% all-electric heat pumps. The heat networks would be fed with residual heat, geothermal energy, aquathermy, and other sources. The draft agreement only mentioned sustainable gases such as hydrogen.

Soon after, in 2019, the Natural Gas-Free Areas Program (PAW) was set up by the government to support municipalities in their transition. This included 27 municipalities that were experimenting with different ways of removing districts from gas, that received a EUR 125 million subsidy, with the purpose of sharing regional results nationally. In addition, two guidelines were published at the end of 2019, one by the Expertise center Heat (Dutch: Expertise Centrum Warmte (ECW)) and the other by Netbeheer Nederland (ECW, 2019; Netbeheer Nederland, 2019). ECW presented a calculation model that presented a 'start analysis,' which concerned a techno- economic analysis of various alternatives to natural gas, showing the (national) costs and CO_2 and energy savings, with figures that were partly based on the Climate and Energy Outlook presented later in 2019. Netbeheer Nederland mentioned the same heat alternatives as ECW - the electric heat pump, high, medium and low-temperature heat network, sustainable gas, and the hybrid heat pump (ECW, 2019). Both these models did not include hydrogen for heating as an option, since they saw hydrogen as likely being limited to a few pilot projects until 2030. This caused significant uproar from the municipalities in 2020, showing that they were interested in hydrogen as a sustainable gas, after which ECW decided to present a renewed database at the end of March 2020 with a more prominent role for hydrogen (De Volkskrant, 2020).

SNM Consideration
At the time, expectations regarding costs were not aligned. On the one hand, Netbeheer Nederland estimated that adjusting the grid to deal with the increased volatility of hydrogen would cost approx. EUR 700 million (Netbeheer Nederland, 2019). Nevertheless, research agency Navigant concluded, in 2019, in a Europe-wide study that the costs for the energy transition could be significantly reduced by continuing to use the existing gas infrastructure with savings amounting to EUR 217 billion per year from 2050 (Navigant, 2019). Around this time there was still debate about the real costs of hydrogen, with misalignment between internal and external parties, which was causing parties to be hesitant to invest. PBL calculated the subsidy intensity for hydrogen production from electrolysis to EUR 1,064, which was expensive compared to other technologies (e.g., floating solar park) which were in the order of EUR 151 per ton CO_2. At the end of 2019 the max subsidy amount was set at EUR 300 per tonne of CO_2, which meant that projects with plans to build a green hydrogen factory had to find an additional European or regional subsidy to lower costs or settle for less efficiency.

Despite the prospect of a more expensive energy bill, research on hydrogen for domestic heating was increasing in the Netherlands, e.g., in Stad aan 't Haringvliet (South Holland), Hoogeveen (Drenthe), Lochem (Gelderland), Tubbergen (Overijssel), Sint Philipsland (Zeeland) and Oldambt (Groningen). As an example, immediately after the new package was announced, in January 2019, the municipality of Hoogeveen in collaboration with 21 parties - ranging from network operators to installers and governments - started a pilot that was co-funded by the government, with the aim of building eighty new homes on 100% green hydrogen (Gawalo, 2019). Reference was made directly to the learning processes of the trial on Ameland.

SNM Consideration
The English Leeds was also a highly influential project that looked into the possibility of heating the entire region, four million homes, with blue hydrogen. The policy evaluation of the example natural gas-free neighborhoods, published in January 2020, showed how difficult and intensive it was to inform residents about the possibilities of using natural gas and then to make them enthusiastic about the best option. In most of the example neighborhoods, no houses were disconnected from the gas network.

Finally, Stedin published a report in Feb 2020, which stated that hydrogen was not expected to play a significant role in heating homes until 2030 (Stedin, 2020). It would not be an optimal solution to provide all homes with hydrogen; the type of house and the location should be considered to determine the best alternative for natural gas. Only in some cases, e.g., in historic city centers, hydrogen would be a better option. Nevertheless, mainly due to governmental support, municipalities thought it was worthwhile to investigate the option. Furthermore, involved parties thought the possibility should be explored so that municipalities could make good choices.

SNM Consideration
The expectations of hydrogen in the built environment were very mixed at this point. On the one hand, hydrogen would be an easy solution to take homes off the natural gas in light of the government's ambitious goals. Furthermore, cheaper solutions such as a heat network had a more negative image. On the other hand, green hydrogen production was in its infancy with very high costs and was expected to remain prohibitive for at least the next ten years, especially for the built environment.

4.5.3 Analysis of key events and influences of the Energy Sector's ESA

Power to Gas as System Function

In the Energy Sector, as described in the previous sections, the key events described in Figure 4.13 can be found. These events have either highly influenced the transition pathway in the Netherlands, or categorize the state that the transition is in. From these key events, sector-specific barriers can be found and they can further be explained by the theoretical framework proposed in Chapter 2. As described by the ESA, these key niche events have been highly influenced by regime and landscape events.

2000 – 2013

After the highly influential Landscape event, the 9/11 attacks, which led to the movement towards less dependence of OPEC in the US, which was closely followed by the EU, research towards hydrogen as a fuel commenced quite quickly (in 2002). Within this period, there were a couple of highly influential regime events, which determined the future development of the niche in the energy sector, most notably the establishment of energy valley and the backing of CCS in 2007 were instrumental for the later development and attraction of hydrogen projects in North-Netherlands. Notable was the concentration of developments in the Northern Netherlands cluster, due to their historical (economic) dependence on gas, which led to significant landscape pressure in the area, and conversely, the expertise and good institutions in place in the area because of this. This quite quickly led to the area's pushing for hydrogen as a replacement for natural gas.

Within this period Landscape pressure on the Regime (as well as regime internal tensions) were pivotal to creating windows of opportunity for hydrogen. This led to voicing of positive expectations towards the niche in a quite early stage, which has contributed in large part to the concentration of development within the clusters. Furthermore, these expectations were made more Robust due to the involvement of internal and external parties with studies that backed expectations with sufficient evidence. The Hyunder study by the EU was instrumental, yet studies by the Energy Valley (with Royal Haskoning DHV) were also influential in guiding the transition forward and attracting pivotal actors to the niche; notably after the Energy Valley results were published, the province of Groningen reconsidered Power to Gas and enter talks with Audi.

2013 – 2020

After the climate movement, it started to seem that in the coming years, Northwest Europe would become a hub for "Power-to-Gas" in the Netherlands. The vast majority of tests and demonstration projects took place there. In the North, major efforts were made on hydrogen because various infrastructures converge there through which synergy effects could be achieved. Electricity from offshore wind farms came ashore, there were a number of large power plants, and Eemshaven had much energy-intensive industry. The region was also known for more than half a century with gas extraction, among the population and knowledge institutes (Gasunie, Hanze University, Energy Academy). In 2016 the period towards practical implementation started. This was also the year the last publication of the Hyunder project was published, which showed that the EU was pushing the development since the EU was first reinforced in 2013 (before the start of the project). Then, in 2015, the Paris Climate Agreement set ambitious goals, which called for a transformation and decarbonization of the energy system in Europe. As a result, it was generally expected that a fundamentally different energy system was needed, in which renewable energy will play a crucial role in the energy mix.

In this period, due to the early investment which came from the historical precedence of Gas in the area (expertise) and the Landscape pressure due to their dependence on gas, implementations centered in Northern Netherlands (and the North-Sea), with the necessary technological development and feasibility studies materializing. Similar to the other sectors, international collaboration (and subsidies) and development within the (industrial) clusters remained pivotal throughout this period. These two aspects came together in the Northern-Netherlands when the European Union made their Largest investment in 2017 through the TSO2020 project, deeming the area the 'European Hydrogen Hub'. This project simultaneously set-in motion the events that led to the construction and opening of the first electrolyser in 2019. Throughout, there has been a clear succession of events where previous learning processes are implemented in future events. This can also clearly be seen in the initial voicing of expectations in the Northern-Netherlands in 2012 about the potential of the North-Sea, which set-in motion the developments that followed, culminating in plans for an electrolyser (1 MW) on a decommissioned gas-platform (supplied with off-shore wind energy) in 2020.

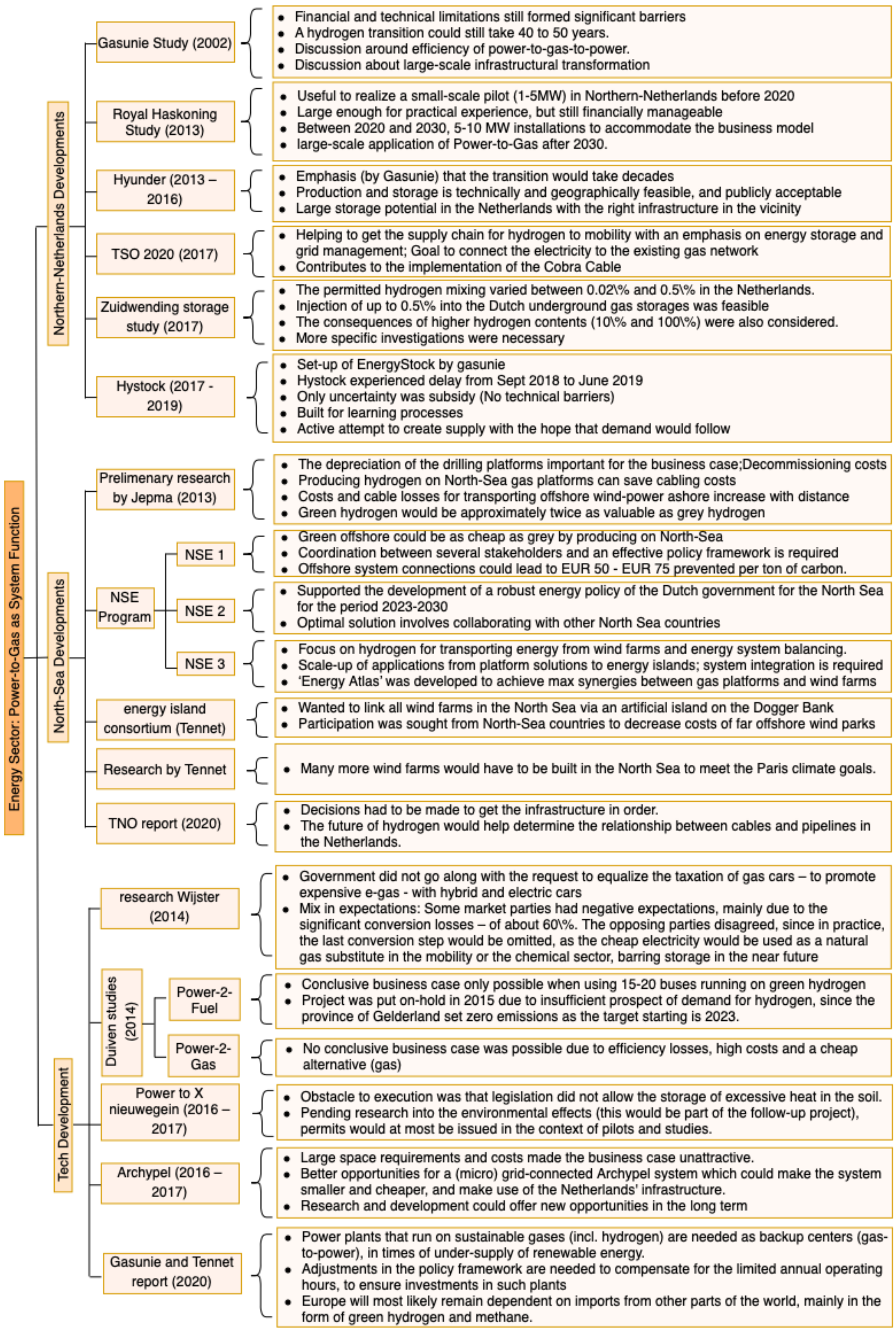

Figure 4.13: Summary of the key niche experimentation outcomes for the Energy sector Power-to-Gas as System function developments

Power to Gas for the Built Environment

In the Energy Sector, as described in the previous sections, the key events described in Figure 4.14 can be found.

2000 – 2013

Within the Built Environment good initial developments can be observed within the first period. Within this initial period, the necessary actors were already active and partnered (most Notably Eneco and Stedin) for the necessary technological development. Good results from this first round of experimentation led to a practical experimentation in Ameland (2008 – 2012). Critical here is the fact that the same actors that got involved from 1998 remained active throughout the entire development (1998 – 2020), which led to the necessary learning processes also being taken into account in successive experimentation.

2013 – 2020

Despite the positive early development, experimentation remained limited within the built-environment. This can be attributed to the fact that there are other (cheaper) alternatives, heightened by the discussion surrounding the actual cost and the fact that the European Union and Dutch Government have not supported the niche as a main option. This has led to rather moderate expectations for the future of hydrogen in this sector. Nevertheless, actors did see a necessity to experiment with the niche, hence they pushed for subsidy for the bottom-up, which has guided the little experimentation that arose.

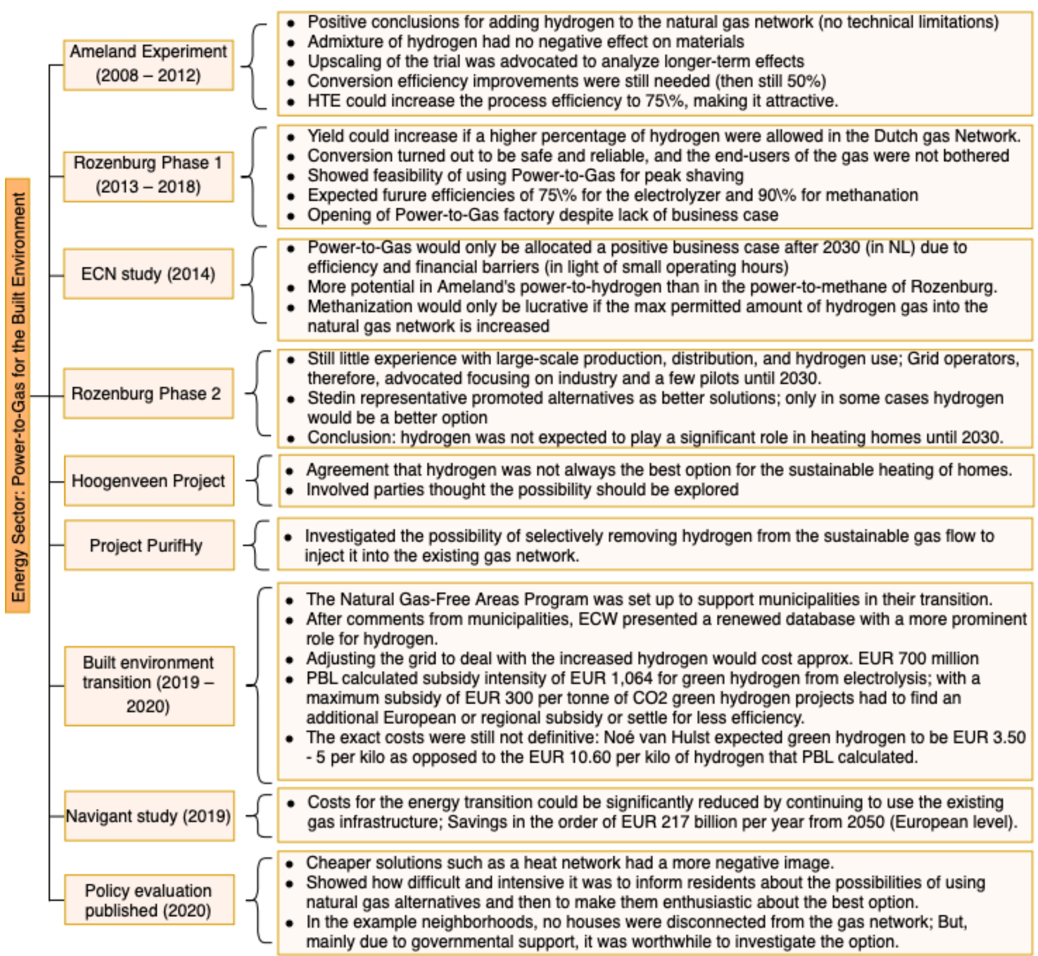

Figure 4.14: Summary of the key niche experimentation outcomes for the Energy sector Power-to-Gas for the Built Environment developments

4.6 ESA of Hydrogen in the Industry Regime: For making raw materials, high-temperature heat and gas plants more sustainable

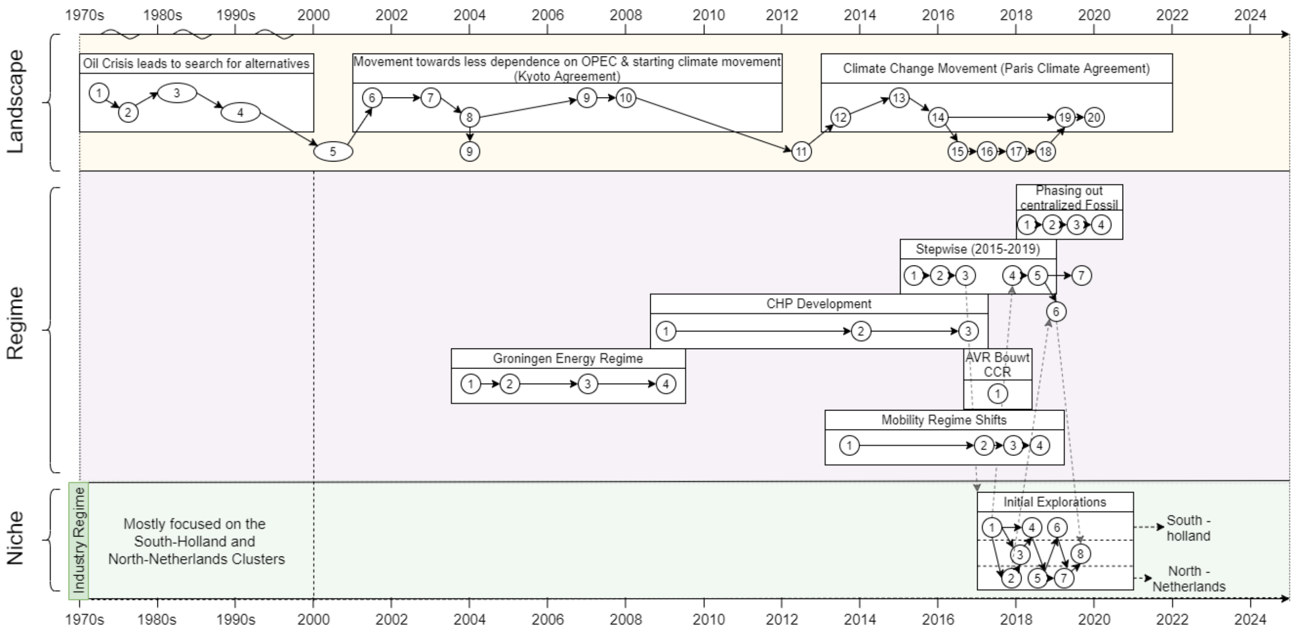

Figure 4.15: Event Map of all relevant events for Industrial application of Hydrogen

4.6.1 2000 – 2013: Initial Development after the need for independence from OPEC

The use of grey hydrogen in the Dutch industry has a long history dating back decades, to before the 1980s, which had made the country the the second largest producer of the energy carrier in Europe (see Chapter 2). The use is concentrated within the five industrial clusters, including the South-Holland Cluster (Rijnmond), the North-Netherlands cluster (Delfzijl), Terneuzen, Geleen and IJmuiden. The developments after hydrogen was started to be seen as a sustainable energy source, which started around the start of the 21^{st} century, in large part due to the need for independence from OPEC, are considered in this section.

This development of hydrogen as a sustainable energy carrier in industry starts with a period of technological development, which approximately spans over a decade (2005 – 2015), which is indicative of the complex and large-scale nature of the transition, especially within this sector. Importantly, within this period, several key stakeholders start getting involved in the niche through independent or partnered research projects and plans. The first one of these research events emerges through a pivotal partnership between the Energy Center of the Netherlands (ECN) and Delft University of Technology (TU Delft), which started research on a hydrogen reactor in 2004 with international funding (Dagblad van het Noorden, 2005; NSE, 2020a). Due to the dwindling subsidy flows in 2008 discussed in section 5.1, which stopped all of ECN's hydrogen research in 2009, in addition to landscape pressure from new government policy (the Research Development Deduction (RDA)) (Rijksoverheid, 2011), ECN had to reorient itself strategically (ECN, 2012).

SNM Consideration
This reorientation led to ECN explicitly focusing on collaboration, which has led to some pivotal lateral sharing of learning processes throughout the development of the hydrogen transition.

Within this period, a pivotal parallel niche development that had much impact on the industry regime, especially on the implementation of blue hydrogen, was Carbon Capture Storage (CCS). This parallel development started with ECN joining a consortium (Cachet) led by oil and gas company BP in 2005 (ECN, 2006), who had recently announced that it was going to invest largely in blue hydrogen production, to research and develop new methods for CO_2 capture (Energeia, 2006), co-funded by the EC. It was around this time that other important parties joined the niche, most notably Nuon's interests started to increase, with the company asking ECN in 2006 to briefly summarize the possibilities and problems with CCS, concerning their ambition to make their new coal gasifier, the Magnum powerplant, located in the Eemshaven 'Capture-ready' (Haije, Jansen, Peters, & Schoonman, 2008). This led Nuon, the Ministry of Vrom, and the province of Groningen to sign an agreement on underground CO_2 capture of the planned Nuon power station in Eemshaven, soon after, in April 2007 (Trouw, 2007).

SNM Consideration
The government's endorsement of the Magnum plans was part of a stream of events in which the government had signaled CCS's promotion in the Netherlands. The government that took office in 2007 had also endorsed the idea of CO_2 capture, asserting that CO_2 capture was necessary because the Netherlands was not yet finished burning fossil fuels, and the country could not afford to wait for newer cleaner fuels (like green hydrogen or solar) to emerge between 2020 and 2050 (De Telegraaf, 2007), after the previous government already provided EUR 80 million from the Borssele fund for this purpose in 2006.

Shell was also starting to get involved at the beginning of 2008, when they formed a partnership with Essent and considered to build a new coal gasification power plant with pre-combustion CCS (De Volkskrant, 2008a). Two parallel developments nudged the initiation of this project: (1) firstly, there were pleas from different committees in 2008, notably, the Energy Council argued for the combination of gasification with CCS (Energeia, 2008) and (2) previous experimentation showed that pre-combustion CCS was cheaper and easier than post-combustion CCS. Shell had made direct referral to the installation of Eon on the Maasvlakte that opened in April 2008 when critcizing post-combustion CO_2.

They had ambitions towards installing a 1000 MW 'CO_2-free power plant' preferably in the southwest of the Netherlands because of the gas to industry; this did not necessarily have to be Rotterdam, however, it was preferred because of the industrial cluster formation, in order to be as close to as many companies and thus potential consumers as possible. Nevertheless, a feasibility study carried out in 2009 showed that the plans were technically feasible, but far too expensive to build.This ambition by Shell and Essent towards implementation in the industrial clusters was part of a broader movement towards active cluster development. Two CCS projects in the South-Holland cluster (Rijnmond region), at the Eon and Electrabel coal-fired power stations, were already going to receive part of the first EUR 250 million in a European subsidy in 2009.

SNM Consideration
Very soon after, near the end of 2009, representatives of both the Northern-Netherlands and South-holland clusters voiced overwhelmingly positive expectations towards CCS, with both representatives envisioning their respective clusters as a potential 'CCS hub' (Energeia, 2009). The main reasonings stemmed from environmental and economic considerations, especially in the Northern-Netherlands due to the Regime destabilizing pressure on the extraction of natural gas. The unique selling point for the Northern Netherlands cluster stemmed from the proximity of all the onshore and offshore gas fields and in the South-Holland cluster the presence of the port of Rotterdam was a plus for sales opportunities for CO_2 by ship.

Finally, as a consequence of the positive voicing of expectations of representatives of both clusters in March 2010, Ecofys was requested by the Dutch government to discover the advantages and disadvantages of coal-fired power stations that burn or gasify coal due to the relative uncertainty around the technology (Energeia, 2010; RIVM, 2010). IGCC was already used worldwide but on a very small scale. In the Netherlands, for example, a Nuon coal gasifier was located in Buggenum and Nuon also intended to install the IGCC technology in combination with CCS at its Magnum power plant (1,200 MW) in Groningen's Eemshaven, as well as Cgen in Rotterdam (800 MW).

SNM Consideration
Near the end of this period, expectations were high, but there was still uncertainty about the most optimal technical design and financial feasibility was still in question.

4.6.2 2013 - 2020: Towards practical implementation after the Climate movement

In the climate movement period (2013 – 2020), it becomes apparent that sustainable hydrogen implementation within the industry sector lagged in comparison to the other sectors. It was after an influential European CCS development (in Norway) had been finalized in 2016, that the Netherlands got involved with their own industry sector plans and developments. Further landscape events, most notably the Netherlands' promotion of off-shore wind to reach the climate goals (announcement in 2016), were highly influential to the (green hydrogen) plans that followed. In the sequences of events after 2016, a distinction could be made between parallel developments (with a distinction between blue and green hydrogen) in and around the South-Holland (Rijnmond/Port of Rotterdam) and the Northern-Netherlands (Eemshave/Delfzijl) Clusters developments and development that had influence on both. In the following subsection, first, the event that mutually influenced both clusters are discussed, then blue and green hydrogen developments are discussed for both clusters separately.

Era of practical research and implementation (2016 – 2020)

At the start of this period, the climate change movement, especially after the signing of the Paris Climate agreement nudged the perpetuation of practical research. Indicative of this was the funding that ECN received, which aided the continuation of research on their hydrogen reactor, which started to run tests in 2016 in Sweden as part of the EU-Project STEPWISE (ECN, 2017; StepWise, 2017). Furthermore, an expectation that arose with the Paris Climate Agreement was that there would be a need for a transitional period in which hydrogen would not always be available. Considering this, DNV GL started researching how natural gas with widely varying quantities could be utilized in the event of shortage, which led to the successful development of a feed-forward fuel-adaptive burner system in October 2015 (DNV-GL, 2015).

SNM Consideration

Due to the 'success stories' this first round of technological development expectations grew more positive. E.g., after the successful completion of the burner system, DNV-GL published a research report that concluded that the production of hydrogen from electrolysis would become competitive with natural gas (DNV-GL, 2019). The report assumed that the use of green hydrogen would become economically feasible due to the increasing share of wind and solar energy in the energy mix.

In June 2017 a highly influential (research) project commenced when research institute TNO together with Berenschot started investigating to what extent the salt caverns at that Zuidwening could be made suitable for large-scale storage of hydrogen, as a consequence of Gasunie's request for the continuation of a Power-to-Gas installation at that site (which became Hystock). This project uncovered a main new insight that the required hydrogen quality differs per application; because low-grade hydrogen is sufficient for the most extensive application markets (power plants and HT heat), the production, distribution, storage, and use of low-grade hydrogen was the primary focus of Berenschot and TNO. This led to them developing a concept where blue hydrogen (natural gas with CCS) would mainly be produced in the large port clusters (Rotterdam, Eemshaven, Terneuzen, Geleen), with CO_2 being transported to North Sea's old gas fields off the Dutch or Norwegian coast by ship or with with part of the high-calorific gas network (Berenschot, 2017; Berenschot, 2017).

SNM Consideration

Importantly, the transition path put forth, focused on using blue hydrogen as an intermediate step towards green hydrogen, by using the existing infrastructure to supply hydrogen for high-temperature heat in gas-fired power plants and industry, and possibly also mobility.

In 2018 an influential report was published by CE Delft which emphasized the urgency of practical implementation of hydrogen (CE Delft, 2018). The report deemed it necessary to make substantial investments, within that decade, starting with the 'blue route' to achieve synergy benefits and create enough market demand and associated infrastructure for green hydrogen (Report – CE Delft). This was necessary since Green hydrogen was still three times more expensive than blue hydrogen (ibid.) and would still need technological development.

SNM Consideration

This report reenforced the 'Hydrogen Coalition' manifesto (May 2018) that was presented to Minister Eric Wiebes (Economic Affairs and Climate, VVD) that put hydrogen as "essential" for the energy transition by concluding that green hydrogen costs could drop sharply over the ten subsequent years (2018 – 2028), close to being competitive with blue hydrogen . From reports, articles, and interviews, in 2018, market parties and (renewable) electricity producers aligned with CE Delft by embracing a hydrogen economy with blue hydrogen as an intermediate step towards green (Energeia, 2018c).

After the release of the CE Delft report in June 2018, several companies simultaneously announced major hydrogen initiatives in October 2018: (1) Nouryon and Tata Steel with the Port of Amsterdam in Ijmuiden, (2) Engie and Gasunie in Groningen and (3) Tennet, Gasunie and Thyssengas in Lower Saxony. In alignment with the report, hydrogen was seen as crucial for the success of the transition from fossil to renewable energy sources

(Energeia, 2018b). Each initiative planned the construction of an electrolyzer with a capacity of 100 MW - a size that was not yet available. Despite the sheer expense of green hydrogen (compared to blue hydrogen), Engie was aiming for a commercial operation in Groningen (Gasunie, 2019), in order to create volume and attracting companies (suppliers and customers) and governments. The choice for Groningen was related to the planned construction of more wind farms above the Wadden, the interconnectors with Norway and Denmark (Norned and Cobra), and the collaboration the company was looking for Gasunie (ibid.).

SNM Consideration
Stakeholders spoke of the importance of viewing the entire supply chain and all different sectors, by calling hydrogen an "Enabler": it would facilitate and create opportunities for other developments ((Energeia, 2018a)).

4.6.2.1 North-Netherlands Cluster Developments (2016 - 2020)

The Northern-Netherlands cluster is relatively young compared to the other four Dutch industrial clusters (Port of Amsterdam – North-Holland, Port of Rotterdam - South-Holland, Zeeland, Chemelot - Limburg). In the 1960s and 1970s, due to favorable regulations (most notably 'Cheap gas') several energy-intensive companies settled in Delfzijl. This was a primary aspect of why establishments that used gas as a raw material were located further south, in Rotterdam, Moerdijk, and Chemelot in Limburg (Groninger Internet Courant, 2000). So, the relative infancy of the cluster formation contributed to the investment in renewable energy and sustainable companies; there were no historically highly fossil dependent facilities like in the other clusters.

SNM Consideration
The cluster had expressed numerous times that it saw hydrogen as having exceptionally high potential (Energeia, 2019a), e.g., during the consultations for the climate agreement, the Northern industrial clusters for the industrial table and regional table - in the Northern Netherlands - had a central message: 'ensure a hydrogen economy'.

North-Netherlands Cluster: Blue Hydrogen Developments
In this period (2013 -2020) the first most impactful development came when the Norwegian government asked oil and gas firm Statoil to conduct a new study on carbon storage as a direct consequence of the Paris Climate Agreement at the end of 2015 - in which carbon capture was seen as an essential tool to achieve the goals. The feasibility studies were completed in June 2016 and formed the basis for the Norwegian government to support the development of subsequent CCS projects in Norway (Energeia, 2016), which Shell and Statoil were running together, with an investment decision by the Norwegian government that came in 2019.

SNM Consideration
The studies indicated that network building would be pivotal for blue hydrogen to succeed since the market was too young to carry out all such projects in competition. This led Statoil to gain interest in involving the entire supply chain and collaborate with other upstream parties; additionally, this formed the reasoning as to why Statoil looked at sales in the Netherlands and the UK simultaneously. Through experimentation in a large hydrogen project in the UK (Leeds), Statoil uncovered that there were still some legal hurdles that needed to be overcome for cross-border transport of CO_2.

As a consequence of many parallel developments, including (1) positive findings in Norway, (2) the announcement from the Dutch government that gas-fired power stations had to be decarbonized in order to achieve the national CO_2 ambition for 2030 (49% CO_2 reduction compared to 1990), (3) the threat of a 'a minimum CO_2 price', which was part of the Rutte III coalition agreement and only affected electricity producers and (4) internal regime destabilizing tensions that arose due to poor performance of the Magnum power plant due to the lackluster Gas (plant) market during this period - Nuon accelerated their plans and announced (in July 2017) that by 2023 the company wanted to switch one of the three units of the Magnum power plant (H2Magnum) in Eemshaven to run on blue hydrogen with CCS in order to move towards green hydrogen (based on wind and solar) around 2030 (Vattenfall, 2017).

Nuon (now taken over by Vattenfall) had since then been investigating the use of hydrogen together with Statoil (experience with CCS in Norway) and with Gasunie (transport and storage) (Vattenfall, 2018). The companies investigated a route in which CO_2 could be transported to Norway by ship or pipeline, with the intended site being developed by the Statoil, Shell, and Total project previously discussed. Support was needed because there would undoubtedly be an unprofitable top. Around this time, publication by Tennet (Dec 2017) showing hat import opportunities of renewable energy were predicted to grow significantly in the years after 2018 with an influx of cross-border connections, especially with Germany (by about 1,800 MW) and Belgium (by about 2,000 MW) (TNO, 2017). This further increased the regime pressure towards gas, causing Nuon to enter a pivotal partnership with TenneT, in mid-2018 to build a so-called 'black start' emergency facility, which added new functionality that ensured that the high-voltage grid would be quickly re-energized after a blackout (Utilities.nl, 2018). After this, Nuon, Gasunie, and Statoil further investigated the possibilities of using hydrogen in the gas plant to generate CO_2-free electricity.

SNM Consideration
Due to the criticism towards CCS, Statoil expressed a need for clear and early communication with stakeholders. At the time, the main argument for CCS was that large volumes of blue hydrogen were needed to build infrastructure (as a justification for investments) necessary for green hydrogen, which was still too expensive and not yet available in large quantities. Furthermore, an adequate supply of cheaper renewable electricity had to become available. This would give the necessary time for cost reduction in electrolysis, necessary learning processes with large-scale use of hydrogen, and accessibility of the infrastructure.

North-Netherlands Cluster: Green Hydrogen Developments
The first major event involving green hydrogen came in Groningen in November 2017, when Groningen Seaports – consisting of the Eemshaven and Delfzijl ports - started the construction of a hydrogen pipeline in Delfzijl, that would bring hydrogen produced by Akzonobel to a hydrogen filling station built by Pitpoint (AkzoNobel, 2018). In accordance with this, AkzoNobel had been engaging in a strategic reorientation since January 2018 in which it wanted to acquire a significant position as a producer of green electrochemical products, with emphasis on production of large-scale hydrogen via water electrolysis.

SNM Consideration
The alignment of expectations and goals, and the network building between Akzonobel and Groningen Seaports led the companies to work together on a "Backbone" for hydrogen, to which 30MW of green hydrogen was planned to be connected to replace grey hydrogen or increase hydrogen demand. Although the pipeline's construction was a small undertaking, the expectation was that it would be a crucial infrastructural basis for Groningen Seaports towards a more significant role for hydrogen in the industrial area; large-scale production of the molecule from sustainable electricity could serve as the basis for green chemistry.

In line with Akzonobel's strategic reorientation towards acquiring a significant position as a producer of green electrochemistry products, in early 2018, AkzoNobel Speciality Chemicals – now Nouryon - together with Gasunie decided to investigate the possibilities for a 20 MW electrolysis unit (largest in Europe), in their green hydrogen project 'DJEWELS' (BioBasedEconomy.nl, 2018). Both companies agreed that the northern part of the Netherlands was well-positioned to develop a green hydrogen economy; due to (1) the large-scale production and import of green electricity, (2) the existing chemical industry, (3) the gas transmission infrastructure, (4) the knowledge infrastructure and (5) the support within the Northern Innovation Board.

In Jan 2020, Nouryon, Gasunie, and four partners (McPhy, BioMCN, DeNora, Hinicio, and SkyNRG) received EUR 11 million European (FCH-JU) subsidies – on top of the EUR 5 million from the Waddenfonds - for which they planned to make a final investment decision for the factory later in 2020 (Energeia, 2020). At the same time, both companies were investigating possibilities to increase the installed capacity from 20 MW to 60 MW and Nouryon participated in the CertifHy project to certify sustainable hydrogen (CertifHy, 2019). Therefore, the 20MW project in Delfzijl (decision in 2020) was a an important steppingstone for electrolysis, since Nouryon had two more ambitious project plans further down their portfolio with pending investment decisions: (1) 100 MW in Ijmuiden with Tata Steel and Port of Amsterdam (Decision in 2021) and (2) 250 MW in Rotterdam with BP and Port of Rotterdam (decision in 2022).

SNM Consideration
Regarding the network building aspect, AkzoNobel and Gasunie complemented each other; they brought together the necessary expertise in the field of gas transport and storage, electrolysis, and handling hydrogen. Furthermore, both parties considered it essential to play an active role in the transition to a CO_2-neutral economy; they saw it as essential for achieving A fully sustainable energy mix by 2050., therefore this project would partly fulfill their sustainable energy goals (AkzoNobel, 2018; Duurzaam Bedrijfsleven, 2018).

Finally, in 2019 Gasunie reported a 2.6% decrease of natural gas transported through the Gasunie network compared to 2018 (Gasunie, 2019), which characterized the internal regime destabilizing tensions due to the pressure on the gas market which led to increased expectations for the hydrogen niche. Notably, on the same day that the annual report of Gasunie was published (Feb 2020), Gasunie, Shell, and Groningen Seaports announced the desire to connect the world's largest cluster of wind farms to a large-scale electrolyzer, under the project name NortH2 (Shell, 2020; Gasunie, 2020). This was further incentivized due to the ambitions of the climate agreement and the Europe green deal, which led the stakeholders to believe that it would be important to make a leap in scale (European Commission, 2019).

4.6.2.2 South-Holland Cluster Developments (2017 - 2020)

At the core of the South-Holland cluster lies the port of Rotterdam, the largest port and industrial complex in Europe and second-largest producer of grey hydrogen (CBS, 2019; Ship Technology, 2013). The large-scale petrochemical cluster, in combination with the high heat requirement of the process industry, which cannot entirely be electrified makes the cluster's transition challenging. In the summer of 2017, the (South-Holland) industry cluster had announced that it was aiming for a reduction of 10 Mton in 2030, through a combination of electrification of low and medium temperature heat, and the use of blue hydrogen for high- temperature heat (Energeia, 2018a). In November 2019, the Rotterdam Climate Agreement was published, which concluded that the goals for tons of CO_2 reduction still needed considerable support (Rotterdamse Klimaat Alliantie, 2019). The most substantial CO_2 reduction would be achieved in the port, through the storage of CO_2 and the closure of coal-fired power stations. Nevertheless, a considerable residual task would remain.

South-Holland Cluster: Blue Hydrogen
In October 2017, the most prominent blue hydrogen project in the South-Holland cluster, h-Vision (formerly Decagas) was announced, concerning a thorough exploration of large-scale decarbonization of natural gas on the Maasvlakte with the removal of CO_2 via existing pipelines for storage in local gas fields or to use Statoil's CCS locations in Norway (h-Vision, 2020), as discussed in the Berenschot and TNO research and the MagnumH2 project. This linked h-Vision to the Porthos project in Rotterdam, which aimed to build infrastructure for the storage of CO_2 in empty gas fields in the North Sea. Immediately, a business model was devised based on the concept to initially use blue hydrogen in (petro) chemistry as raw material and as a fuel for underfiring and electricity production instead of coal. Matters that were previously researched in the ROAD CCS project (Rotterdam Storage and Capture Demonstration Project) of Uniper and Engie Energie were used in this concept (European Commission, 2020b).

SNM Consideration
The busines model was validated by the Wuppertal institute who previously conducted a study for the Port of Rotterdam Authority and financed by TNO with its resources and a subsidy from Deltalinqs - the association of Rotterdam port companies. Furthermore, in 2017, 16 parties joined the platform, including energy producers, hydrogen producers, Gasunie, Port Authority, municipality, Deltalinqs and Ministry of Economic Affairs.

Subsidy from the Netherlands Enterprise Agency (RVO) was lent for a feasibility study in summer 2017, which focused on the technical, economic, and financial feasibility of the project. The study (July 2019), next to showing the immense emissions reduction that could be achieved in the port (2 to 6 Mton of CO_2), concluded that almost the entire concept could be implemented with standard available technology and utilization of existing assets (Port of Rotterdam, 2019a; h-Vision, 2019). Thus, in 2019 there were no more technical research questions about production, capture, and storage (ibid.). Financially, however, there were still some hurdles to overcome, for which H-Vision attributed the government with the role of taking responsibility and assisting with subsidies to absorb the unprofitable top.

In the meantime, many decisions would still have to be taken, for example, on the participating parties' roles and who would own the production facilities. There were also questions about the technical design and financing. An investment decision would be made in 2021 (report). In this scenario, the first installation could supply blue hydrogen from 2026. Whether this planning could be achieved depended mostly on political choices about CCS and subsidies. To conclude, h-Vision was similar to the plans for the Magnum power plant and also had similarities with the concept of TNO and Berenschot in terms of ambition and scale; this also meant that the projects both had the same bottleneck that they were expensive.

SNM Consideration
In line with the CE Delft research report published in June 2018, these projects also assumed a start-up with blue hydrogen for a transition to green hydrogen (towards higher quality expectations). Their reasoning was also the same: by starting with blue hydrogen, it becomes possible to invest in the infrastructure and conversion of installations necessary for the industry to switch to green hydrogen (backed by 'sufficient' evidence). Furthermore, the learning processes from the feasibility study helped specify the demand for the government; there would be an unprofitable top, which the companies preferred to see financed by the government.

South-Holland Cluster: Green Hydrogen
In Rotterdam, the first direct developments concerning green hydrogen would also come in 2017 with the Power-2-Gas-2-Refineries project in which research was conducted for the realization of a 20 MW electrolysis installation for the BP refinery in Rotterdam, using wind energy that would land on the Maasvlakte (Smart Port, 2017). Similar to the h-Vision project, the study concluded technical feasibility, but there were still hurdles that would have to be overcome for economic feasibility: (1) Green hydrogen should be recognized as a renewable fuel, and (2) no energy tax should be levied on the mains connection for electrolyzers.

SNM Consideration
TNO had researched the technical and economic feasibility of using green hydrogen for these refining processes because, according to the research institute, hydrogen was crucial for all 'Deep Decarbonisation Pathways.' after this research, big Dutch multinationals including Shell and AkzoNobel gained interest in green hydrogen. September 2017 saw the announcement of a 10 MW PEM electrolyzer that Shell was going to install in its oil refinery (called Rheinland refinery) in Wesseling, Germany. Shell had expressed positive expextations about Power-to-Gas' system function. Furthermore, AkzoNobel had soon after also announced a Waste-to-Chemicals plans with the supply of hydrogen in Feb 2018, with plans of further upscaling of water electrolysis for the development of bio-based chemistry value chains for making carbon chemistry more sustainable. According to the company, Bio-based routes to chemical products required the use of green hydrogen.

A direct follow-up to the Power-2-Gas-2-Refineries project, as part of the Port's plans to reduce the CO_2 emissions in the wake of the Rotterdam Climate accord (2019) showing that current plans were insufficient, was the feasibility study announced in April 2019 into the production of green hydrogen for the Rotterdam refinery of BP with a 250 MW electrolyser, with which the refinery's CO_2 emissions could decrease by about 15% in the long term (Ministerie van Economische Zaken en Klimaat, 2018; Port of Rotterdam, 2019b). Nouryon would manage any electrolysis installation to be built.

The industry in the Rotterdam port region was responsible for 20% of Dutch emissions in 2019. According to Port of Rotterdam Authority (HBR), electrolysis installations with a capacity that were ten to thirty times higher than the installation for BP would have to be built to make the port CO_2 neutral by 2050. Therefore, in April 2019, HBR was also investigating the possibility of an electrolysis capacity of 2 GW (Port of Rotterdam, 2020), in a large-scale consortium with, among others, Nouryon, Shell, and the other port companies and the provinces of North and South Holland and Groningen.

SNM Consideration
Experts have tempered high expectations around hydrogen because development is expensive. Nevertheless, hydrogen was seen as an indispensable means of significantly reducing emissions in the port of Rotterdam. These plans were seen as indicative of Rotterdam's potential of being a frontrunner in the energy transition, specifically hydrogen developments were a distinguishing factor for the industry in the port area.

4.6.2.3 Additional highly influential development: Subsidy discussion (2017 - 2020)

Blue Hydrogen Discussion
The subsidy discussion around hydrogen initiated with the MagnumH2 plans in 2017 and has since then had a significant influence on the overall transition pathway in the Netherlands. At this time in 2017, the subsidy scheme that Nuon could apply for, was also still unknown to the company itself (Vattenfall, 2017), which led the company to enter in talks with the government about subsidy options for hydrogen in March 2017, however, Nuon was unable to report results in July 2017. Nevertheless, at the time, a Ministry of Economic Affairs spokesperson expressed that hydrogen did not fit in the SDE+ scheme since it is an energy carrier, which had to be made with energy sources, which were already subsidized via SDE+ (Energeia, 2017b).

SNM Consideration
Industrial stakeholders pointed out that the Netherlands lagged in blue hydrogen projects as opposed to e.g., Norway due to a lack of a CO_2 price. TNO attributed this as a primary reason as to why, in summer 2017, even with hundreds of millions of grants awarded, Engie and Uniper decided not to invest in the storage of CO_2 from their Rotterdam coal-fired power stations in old gas fields under the North Sea - the same company that after- ward had plans to invest in green hydrogen in Groningen. The companies then concluded that financing and infrastructure were the main bottlenecks for CCS in the Netherlands.

Later, from the conclusion of the h-Vision feasibility study (July 2019) it became clear that there were mostly financial hurdles to overcome, with subsidies being necessary to absorb an unprofitable top. In September 2019, the initiators pronounced that h-Vision could not proceed if the SDE++ subsidy towards CCS were not increased (Berenschot, 2019; Ministerie van Economische Zaken en Klimaat, 2020). The necessary amounts were calculated by PBL (assigned by the government) to be no more than EUR 67, as opposed to an estimated EUR 86 to EUR 146 cost per tonne of CO_2 avoided by h-Vision.

SNM Consideration
Much backlash had arisen after the PBL calculations, which rendered several large-scale hydrogen projects infeasible. Fourteen companies had then (Aug 2019) sent a joint letter to the government in the hope that adjustments could still be made (Energeia, 2019b). As a result, the four coalition groups (VVD, ChristenUnie, D66 and GroenLinks) showed enough flexibility to enter dialogue with both the industry and the energy sector (ibid.).

After a lobby from the business community and an appeal from the House of Representatives, the government had instructed PBL to redo the calculations with different parameters (PBL, 2020); the maximum support in the SDE++ was calculated to be EUR 106. h-Vision industrial parties still expressed concerns about the feasibility due to the SDE++ subsidy still not covering the unprofitable top; the SDE++, in various categories that would be opened up to CCS, assumed the use of hydrogen as a raw material, while projects like h-Vision focused on replacing natural gas as fuel. As a result, only the additional costs for the capture and storage of CO_2 would be subsidized, and not the construction and operation of the reforming installation for hydrogen production.

SNM Consideration
The government previously explicitly mentioned h-Vision as one of the projects that it would actively support. However, actors involved in h-Vision (e.g., Equinor, TNO and Deltalinqs) did not see this reflected in the translation towards this subsidy (Ministerie van Economische Zaken en Klimaat, 2020).

Green Hydrogen Discussion

In September 2019 it was confirmed that electrolysis would not be included in the SDE++ scheme in 2020, since the electricity needed from the grid was nowhere near climate neutral, which meant that there were much more effective ways to reduce CO_2 emissions. The government advocated to stimulate green hydrogen in other ways, mainly mentioning the DEI scheme as an alternative for demonstration projects (Ministerie van Economische Zaken en Klimaat, 2019). Criticism from various companies showed that opinions differed; there seemed to have been a consensus within the industry that electrolysis should be subsidized.

After the market research by the government, it was announced in Feb 2020 that hydrogen would nevertheless be included in the first subsidy round (total EUR 5 billion) of the SDE++ (29 Sep 2020 – 22 Oct 2020). Nevertheless, industrial parties expressed that the maximum subsidy amount would still not cover the unprofitable top of electrolysis. The question remained to what extent initiators of green hydrogen projects would be helped with this (Waterstof Coalitie, 2019). A necessary amount of EUR 10.60 per kg of hydrogen produced came from the PBL's original calculations, which had been reduced to just over EUR 4 after the government had instructed PBL to redo the calculations. In such a case, the SDE++ would cover part of the unprofitable top and the rest had to come from European or regional subsidy or with a lower return.

There was considerable interest in using hydrogen in the oil industry, since a fuel supplier could meet the obligation to transport under the Renewable Energy Directive in this way, instead of applying ("downstream blending") biofuels (Uniper, 2016). However, the European Commission did not recognize this option in the latest version of the Directive; According to the European Commission's guidelines, green hydrogen only counted when used in fuel cell vehicles or after methanation. Bringing hydrogen under the Gas Act would make hydrogen transport a task of a public grid operator, with a separation between hydrogen production and hydrogen transport, and transparent conditions for feeding into this grid. This also affected h-Vision, where hydrogen from natural gas with CCUS was central.

4.6.3 Analysis of key events and influences of the Industry Sector's ESA

In the Industry Sector, as described in the previous sections, the key events described in Figure 4.16 can be found. These events have either highly influenced the transition pathway in the Netherlands, or categorize the state that the transition is in. From these key events, sector-specific barriers can be found and they can further be explained by the theoretical framework proposed in Chapter 2. As described by the ESA, these key niche events have been highly influenced by regime and landscape events.

2000 - 2013

Within the initial period, which is characterized by the search for alternatives for OPEC (kicked-off by the 9/11 attacks in 2001), there was a lack of practical experimentation in the industry sector. Nevertheless, due to the large-scale nature of the niches in this sector, initial technological development was key in moving the transition forward. As a result of this, key actors, like ECN, TU Delft, NUON, the government Shell, Essent, BP and the European Commission became involved with the niche and key partnerships are formed; these are the same actors that guide the transition forward in the following period. Within this period, the parallel niche development of CCS was pivotal in attracting some of these partnerships and increasing expectations towards blue hydrogen as a transition option towards green hydrogen.

These partnerships and CCS led to the first expression of ambitious plans, e.g., in 2007 by Nuon, which later became the ambitious H2Magnum project. Regime developments also created windows of opportunities which nudged decision-making towards hydrogen, most notably the pleas from different committees in 2008, notably, the Energy Council who argued for greening of the gasification process. Through the technological development due to the positive expectations that arose in the beginning of this period, near the end of the period, feasibility studies began to show technical feasibility, yet plans were too expensive. In part due to this, it started to become clear that clustering would be essential and the industrial clusters themselves began to actively promote it. Finally, the government took on the role of having the facts sorted out, as a consequence many market parties and the clusters expressing positive expectations. So, near the end of this period, expectations were high, but there was still uncertainty about the most optimal technical design and financial feasibility was still in question

2013 – 2020

Within the second period, which is characterized by the climate movement (kicked-off by the SER accord in 2013), the landscape sector developments lagged compared to the other sectors, due to its dependence on international collaboration. Only after the Paris climate agreement at the end of 2015, the continuation of technical research was nudged. This proved to be pivotal, since the uncertainties about technical design from the previous period were mostly overcome, which directly led to growing expectations by industrial parties. E.g., after the successful completion of a burner system, DNV-GL published a research report that concluded that the production of hydrogen from electrolysis would become competitive with natural gas. After this, practical experimentation (2016 – 2020) is kicked-off by an international parallel niche event, the completion of a big CCS project by Statoil in Norway in 2016, which is indicative of the importance of international collaboration within this sector.

After this project the transition within this sector distinctly developed within the big (industrial) clusters in the Northern-Netherlands (around Eemshaven and Delfzijl) and South-Holland (around Rijnmond (Port of Rotterdam)), with some projects have mutual influence on both. This period brought with it multiple ambitious plans and feasibility studies within the respective clusters, most notably h-Vision, MagnumH2 and a plan by TNO together with Berenschot (all initiated in 2017). These plans had many similarities (including similar actors), with them all mentioning the Statoil study in Norway and all focusing on the 'blue route' (backed by evidence from CE Delft in 2018), with an initial focus on blue hydrogen to create the demand and infrastructure necessary to implement green hydrogen on a large scale when it becomes economically feasible (around 2028). Their similarity also meant that they had a similar bottleneck; they were all very expensive and had an unprofitable top that they preferably saw covered through government subsidy (SDE++). The draft SDE++, nevertheless would provide too little SDE++, which has led all of these plans to remain feasibility studies.

This sector has been guided by Landscape and regime influences, which have opened window of opportunity for the niche; (1) the turmoil that the Oil and Gas regime experienced, (2) the announcement from the Dutch government that gas-fired power stations had to be decarbonized, (3) the threat of a CO_2 price, and (4) the government's endorsement of wind energy (2016), directly led to hydrogen plans, most notably the MagnumH2 project (2017) by Nuon and afterwards, Gasunie's ambitious NorthH2 hydrogen plans (2019) in the Northern Netherlands. Finally, after these highly influential plans, Landscape pressure from the climate movement with plans for CO_2 neutral ports by 2050, actors saw a necessity for larger scale plans with hydrogen, which was further incentivized due to the Europe green deal. Therefore, the number of plans for companies for ever- larger electrolyzers increased rapidly, firstly culminating in three green hydrogen projects of approximately 100 MW electrolysis and planned 250 MW blue hydrogen installations in both clusters in 2019 and finally plans for a 2 GW plant in the Port of Rotterdam. Nevertheless, due to the financial barriers, not one of the projects had yet been realized, and it was often even a matter of waiting for the investment decision.

Conclusion

In conclusion, within the Industry regime there are three main initiatives that emerged for large-scale hydrogen production from natural gas with CO_2 capture and storage for use in gas-fired power stations and the petro-chemical industry for high-temperature heat and feedstock. (1) The first one concerning the Magnum power station is the most concrete. (2) There is overlap between the companies involved in the hydrogen project for the Magnum power plant and in h-Vision (Lateral Network). This allows the projects to support and reinforce each other (positive sign from an SNM perspective). (3) A third initiative that affects both is from Berenschot and TNO. This is a more generic concept, with the same transition vision and technical principles, but without the effect on specific power plants. From the ESA can be seen that there have been contacts between the initiatives, but these were separate plans, which are not mutually exclusive. Additionally, the (petro) chemical industry, at a very early stage has positive expectations and sees opportunities for the development and application of new technologies and associated business models for the conversion of renewable solar and wind energy into heat, hydrogen and chemicals. In addition to energy storage, direct use of this energy in industry could help to cope with peaks in the energy supply from renewable sources. Nevertheless, financial barriers are currently holding back large-scale implementations.

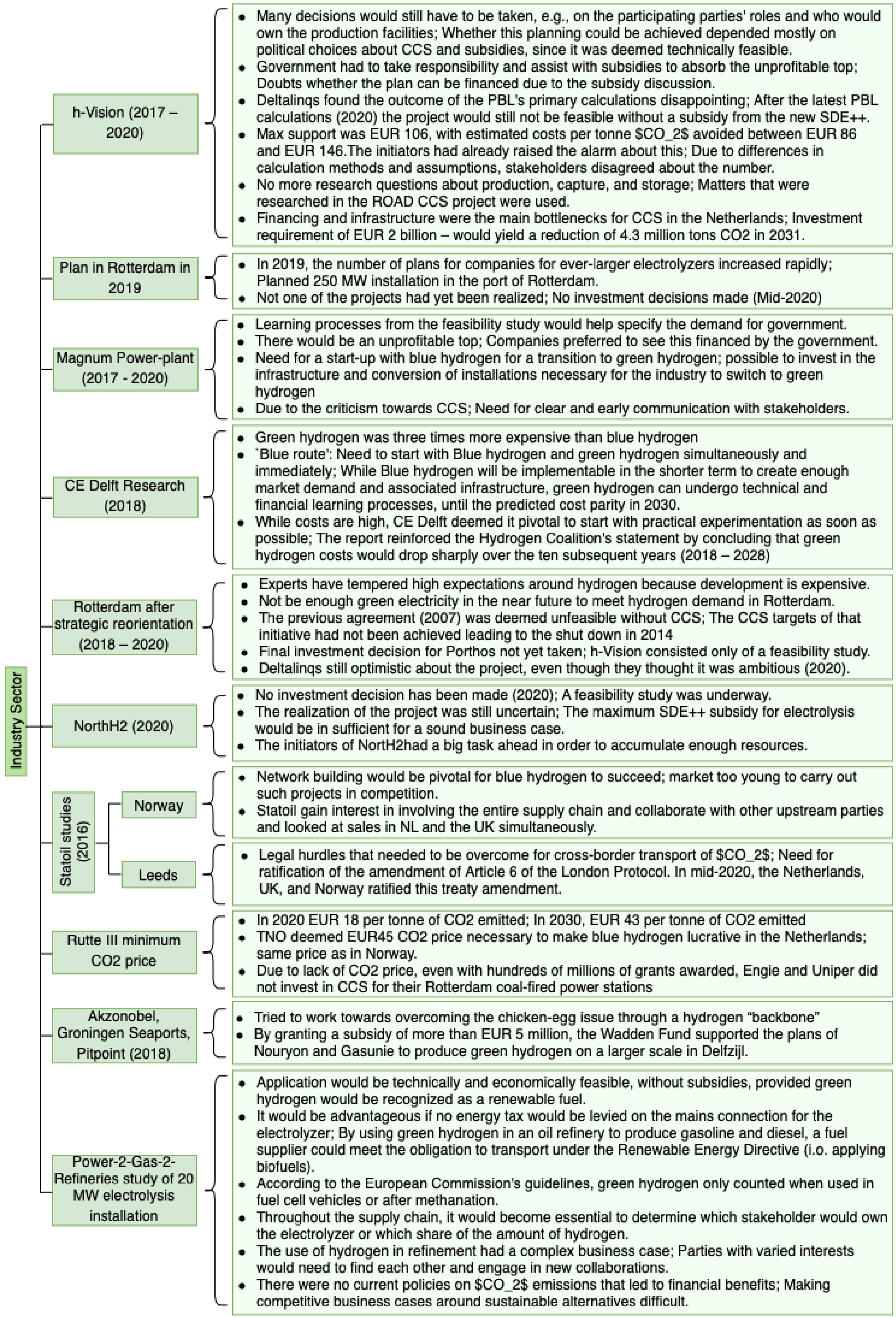

Figure 4.16: Summary of the key niche experimentation outcomes for the Energy sector Power-to-Gas as System function developments

4.7 Conclusion of the ESA: Barriers towards hydrogen niche implementation

From the ESA, it can be concluded that there are two types of barriers that are holding back the niche (from a non-theoretical perspective). These a subdivided into (1) technological Barriers and (2) Financial Barriers. As can be seen by Figure 4.17, the financial barriers far outweigh the technical barriers. In this section, the underlying reasons will be addressed in short.

4.7.1 Technological Barriers

4.7.1.1 Technological and Geographical limitations

When it comes to hydrogen, most technical barriers concerning production, storage and distribution have mostly been solved over the period of the ESA. Within the mobility sector, initially there were some technical limitations where experimentation in the CUTE project (2003 – 2008) showed that hydrogen fuel cells did not have a long enough lifespan causing frequent failures. However, these issues were mostly fixed after 2012, when GVB implemented new buses in Amsterdam, and the old buses were refurbished and successfully drove in Eindhoven in 2017. Furthermore, in 2016 many Fuel-Cell Electric buses had already been implemented in various countries in Europe, Canada, and the USA, with low availability almost always stemming from control issues and hybridization strategies rather than problems in the fuel cells themselves.

Furthermore, within the energy sector developments, experimentation has showed that technical feasibility of e.g. underground storage is possible without many technical enhancements to the salt caverns and transportation through the natural gas network would also only require reinforcement of sporadic nodes in the system. From a geographic perspective, the climate movement which called for the increase of intermittent renewable energy brought with it a need for more storage and the necessary space to achieve this. Through the Hyunder research, firstly it became clear that underground storage was geologically feasible and acceptable to the public and secondly, it became clear that the Netherlands had an advantage due to it containing several usable salt caverns with the right infrastructure in the vicinity.

4.7.1.2 Hydrogen is an energy carrier that always has to be produced

Hydrogen is an energy carrier that always has to be produced, which means that there are (conversion) losses attributed with the process and there is a need for (increased) renewable energy supply. There are still significant losses when converting from Power-to-Gas-to-Power, with approximate efficiency of 60% for each of the conversion steps. Experimentation in the built environment, first in Ameland (2008 – 2012) and the in Rozenburg (2014 – 2020), emphasized efficiency as a main issue, with the general conclusion that the efficiency of electrolysis could increase to 75% in the near future (and 90% for methanation), which would make it more attractive. In addition, there are also transport losses of bringing wind-power ashore, which is core to the NSE program.

Attributed to the second issue (need for renewable energy), especially at the start of the development in the early 2000s, there was not much supply (4% in 2013), which held back experimentation. The urgency of that agreement in addition to the Climate Paris Agreement has increased the share to 6%, which is still insufficient. This lack of renewable energy forms a significant barrier particularly towards green hydrogen, which further enforces the efficiency barrier, since the produced electricity should be used as efficiently as possible. Furthermore, predictions show that there would not be enough green electricity in the near future to meet the Port of Rotterdam's huge hydrogen demand.

4.7.2 Financial Barriers

4.7.2.1 Sheer Expense of projects and objects

As uncovered by the ESA, from multiple (feasibility) report conclusions and expressions by prominent stakeholders, financing is the main bottleneck for both blue- and green hydrogen in the Netherlands, which affects every aspect of the implementation, from infrastructural developments to CCS implementation; the switch from fossil energy to electricity combined with hydrogen would mean a significant switch-over that would require major investments. As reported by CE Delft (2018), even though the costs of green hydrogen could drop sharply over within this decade, it is essential to make substantial investments in a hydrogen economy immediately starting with the 'blue route' to create enough market demand and associated infrastructure for green hydrogen (Report – CE Delft). That is because a major challenge is the need for an infrastructure that still has to be built, while simultaneously attracting enough demand.

Next to the cost of hydrogen production, due to the infancy of the niche, associated technologies are also still expensive. Take for example hydrogen buses: Even though they have undergone 20 years of development for which the ESA shows a steady price drop (due to increased optimization), they are still approximately four times as expensive as internal combustion buses and twice as expensive as its battery-electric counterpart. Nevertheless, VDL's expectation was that hydrogen buses would be able to compete with diesel buses within 5 to 10 years if niche experimentation continues steadily. This barrier is further re-enforced due to the expense of high-pressure refueling due to decentralized production of hydrogen in small units. Furthermore, for the energy sector, ECN concluded that Power-to-Gas (Power-to-Gas) would only be allocated a positive business case after 2030 in the Netherlands due to significant energy losses and substantial capital-intensive investments concerning the small number of operating hours that the installations would make. Finally, the expense of transforming houses to hydrogen should be seen through the lens that the whole energy system would be transformed, which leads to systems' savings and savings from keeping the natural gas grid (EU 200 billion yearly in 2050).

Expense makes investment decisions hard
The high costs of hydrogen projects have formed a significant barrier to investments decisions over the ESA between 2000 and 2020. This can be seen by the fact that even though there have been ambitious goals over the years, investment decisions have usually not followed, due to the sheer expense of the investment. Over the course of the ESA, there have been multiple example of this, with the first one coming in the Industry sector, with ambitious plans by Shell and Essent in 2008, which proved to be too expensive. After this there have been a plethora of increasingly ambitious plans, culminating in planned 250 MW and 2 GW installation in the port of Rotterdam in 2019 and equally ambitious plans in Northern Netherlands by large companies including Gasunie, AkzoNobel and Shell (e.g. NortH2), yet not one of the projects had yet been realized, and it was often even a matter of waiting for the investment decision. This, in combination with the cabinet proposals for the new SDE ++ scheme, for which subsidy for electrolysis would be far from sufficient for a sound business case, makes the investment decision risky for the initiators. Finally, in the energy sector multiple plans were canceled, especially at the beginning of the climate movement period (2013 – 2020) (e.g., 12 MW in Wijster) and feasibility studies came to the conclusion that there was no business case due to the high costs and cheap alternative. After these failed attempts, it becomes clear that the prospects for hydrogen increase, nevertheless still with a financial barrier attached to it.

Expense causes actors to question whether projects are commercially interesting
In the early 2000s already, actors stated concerns about whether new technologies such as hydrogen fuel cells were commercially interesting enough to be applied on a large scale, due to the high costs. Later, when practical plans for large-scale blue hydrogen production surfaced, with projects like h-Vision and Nuon's Magnum CCS project, they had the same bottleneck that they were expensive. According to these actors, in all likelihood, there would be an unprofitable top, which the companies preferred to see financed by the government. As a consequence, experts have tempered high expectations around large-scale hydrogen plans, like the plans for a 250 MW for the Rotterdam refinery of BP, due to the expense.

Issue of cheaper alternatives
Cheaper alternatives, such as Electric buses in mobility or all-electric heating or waste-heat in the built environment also make investment decisions hard. In these cases, investment decisions by individual parties would be easier to make towards these cheaper alternatives, nevertheless, due to the high expectation for hydrogen, parties are still hesitant to invest in those options. Furthermore, they also have their own drawbacks; All-electric might be a local optimum solution, which isn't globally optimal, making it more expensive in view of the entire country, and waste-heat comes with a bundling necessity in which groups of houses are interdependent, giving it a more negative image. Finally, as can be seen in the Mobility sector ESA, it is up to the Dutch government and the European Union to facilitate hydrogen buses, due to their system benefits, since without (market) niche protection, companies like VDL still saw battery-electric buses as the best option in urban public transport.

Need for substantial market demand in order to be profitable
Due to the expense of projects, there is a need for enough demand for the business model to be profitable. This can be seen by the Statoil study in Norway (2016), which indicated that network building would be pivotal for blue hydrogen to succeed since Statoil expected that the market was too young to carry out all such projects in competition. This led Statoil to gain interest in involving the entire supply chain and collaborate with other upstream parties, directly leading to collaboration with Nuon, Gasunie and Tennet (MagnumH2). In 2018 actors spoke of the importance of viewing the entire supply chain and all different sectors, by calling hydrogen an "Enabler": it would facilitate and create opportunities for other developments (MARCEL GALJEE, director of energy Nouryon). Throughout the ESA there are some examples of necessary cross-sector interconnectivity to increase demand, e.g., in 2014 when Audi and Groningen discussed plans for a Power-to-Gas plant that would be used for mobility and energy purposes. Another example came in 2019 when AkzoNobel and Groningen Seaports collaborated with Pitpoint to supply hydrogen to 2 buses.

4.7.2.2 Large Scale Nature of the Transition

Need to reform infrastructure on the necessary scale
This barrier has to do with the large-scale nature of the hydrogen transition. In order for the transition to be successful (due to the high costs and the huge transformation), the entire infrastructure should be transformed. Once this is done, the country would remain 'stuck' with it, similar to the natural gas infrastructure, which was built in the 1960s. In essence, it is up to market parties and, most importantly, the government to make an informed decision on whether this is the right pathway, and afterwards be all-in for the transition to be lucrative. When this decision is made, e.g., the government should be clear in stating their position, in order for market parties to be able to make investment decisions more easily.

Hard to have practical experimentation on the necessary scale
Due to the Large-scale nature of the transition, throughout the ESA, especially in the Energy and Industry sectors, it has become difficult to experiment on a relevant scale. In a Royal Haskoning DHV (2013) study, the authors concluded that only between 2020 and 2030, a few installations of 5 to 10 MW could be realized to allow a business model to "come to fruition," after which large-scale application of Power-to-Gas would be provided for the period after 2030 (ibid.). Additionally, due to the high costs, despite actors expressing the necessity of a testing ground (Energy Island) in the North-Sea, none has yet been created. Furthermore, within the built environment, there have also not been many tests yet, next to Ameland, Rozenburg, Hoogeveen and Stad aan 't Haringvliet. This also led the European union to get involved with the Store&Go project in 2016 to start investing on a larger scale in Power-to-Gas (after many failed attempts by individual countries).

4.7.2.3 Legislative Barriers

Need for increased and standardized percentage for hydrogen injection in the natural gas grid
Experimentation in the Energy sector, specifically the built environment study in Ameland (2008 -2012) has shown in an early stage that there were barriers to hydrogen utilization within the gas system due to limits on

the gas composition. Through experimentation the study concluded that sustainably produced hydrogen can be added to the natural gas network without any problems (Stedin, 2012) without demonstrable influence on piping materials and gas appliances. The follow-up, Rozenburg (phase 1), also showed that the yield could increase if a higher percentage of hydrogen were allowed in the methane in the Dutch gas Network (government role) (ibid.). Finally, the same study from ECN in 2014 that concluded that Power-to-Gas was still not lucrative, concluded that, only when the maximum permitted amount of hydrogen gas would be injected into the natural gas network opportunities could arise to methanate the hydrogen gas using CO_2. Finally, in 2017, there was no standardized percentage for hydrogen injection in the grid across the country yet. The permitted hydrogen content within the Dutch gas distribution system varied in respective parts of the country between 0.02% and 0.5%. The findings from a study in Zuidwendig showed that injection of up to 0.5% into the Dutch underground gas storages was feasible for caverns and porous reservoirs.

Need for coordination between stakeholders and effective policy framework

Within the Energy sector ESA, specifically within the North-Sea developments, the NSE1 results showed that there would be a need for coordination between several stakeholders and an effective policy framework to translate system connections into business cases in order for green offshore hydrogen to become as cheap as grey. The NSE 3 results give similar recommendations, where an optimal solution would involve looking at different systems and collaborating with other North Sea countries, coastal provinces, ports, and industrial clusters. Other legal hurdles relating to cross-border transport of CO_2 were uncovered in the industry sector ESA, through the international hydrogen project by Statoil in Leeds. The most important hurdle was the need for ratification of the amendment of Article 6 of the London Protocol, which still acted as a barrier to transporting CO_2 across borders for permanent offshore storage. Nevertheless, the Netherlands, UK, and Norway were the only countries to have ratified this treaty amendment to the London Protocols. Finally, within the Energy sector ESA, Gasunie and Tennet's study (2020) showed "adjustments in the policy framework are necessary" to ensure that investments are made in power plants that run on sustainable gases, such as hydrogen, which are going to be needed increasingly as backup centers (gas-to-power), in times of under-supply of renewable energy.

Netherlands' subsidy discussion

In 2019 it became clear that the government had to take responsibility and assist with subsidies to absorb the unprofitable top. Blue hydrogen projects, such as h-Vision depended greatly on political choices about CCS and subsidies; in September 2019, h-Vision expressed that it could not proceed SDE++ subsidy towards CCS was not increased. Furthermore, it was announced that electrolysis was not going to be included in the SDE++ at the time. After the omission of electrolyisis and CCS PBL calculations (Sep 2019) were received with backlash from industrial parties, electrolysis was later added and the calculations were asked to be revised by the government. Nevertheless, there is currently still much debate regarding both subsidy amounts (for electrolysis and CCS) which are planned for the (oct 2020) SDE++. Currently h-Vision's plans are still infeasible with this subsidy and the initiators do not agree with the assumptions made during calculations, since they assume the use as raw material as opposed to it as energy carrier that replaces natural gas. For green hydrogen, PBL's new calculation showed that an optimum would be reached at 2,000 full load hours (i.o. 8000 full load hours). Because of this the question remained to what extent initiators of green hydrogen projects would be helped with this.

Adjustment in Policy framework is necessary

A report by TNO (2020) explicitly pointed out that decisions had to be made to get the Netherlands on- and off-shore infrastructure in order. The future of hydrogen would help determine the relationship between cables and pipelines in the Netherlands. The expectation grew within the Dutch Government that hydrogen would have to play an essential role in future climate policy, due to the system function and the preservation of the gas network for financial reasons. The gas producers saw an opportunity to use the extensive pipeline network on land and at sea to transport hydrogen.

Green hydrogen is not recognized as a green fuel

The Power-2-Gas-2-Refineries of a of 20 MW electrolysis installation concluded that the application would be technically and economically feasible, without subsidies, provided green hydrogen would be recognized as a renewable fuel. By using green hydrogen in an oil refinery to produce gasoline and diesel, a fuel supplier could meet the obligation to transport under the Renewable Energy Directive instead of applying biofuels. However, the European Commission did not recognize this option in the latest version of the Directive; according to the European Commission's guidelines, green hydrogen only counted when used in fuel cell vehicles or after methanation. According to TNO, there would also be more willingness to invest in companies if upstream blending were honored under the Directive, and if the regulations for hydrogen were also in order. Bringing hydrogen under the Gas Act would make hydrogen transport a task of a public grid operator, with a separation between hydrogen production and hydrogen transport, and transparent conditions for feeding into this grid.

Necessity of standards
Interoperability of hydrogen filling stations was ensured in 2017 by introducing a Dutch standard according to the European standard design "EN 17127 Gaseous hydrogen - Fueling stations - Part 1: General requirements". This had a direct effect on the ability of the Netherlands to receive European funding (through the TEN-T project). This, in turn, had a direct link to the fact that in September 2018, the Netherlands had been given the opportunity to subsidize seven petrol stations in the Netherlands via the TEN-T project BENEFIC.

4.7.3 Consequence of both Financial and Technical Barriers

Because of financial and technical limitations, the consensus is that the transition to a hydrogen economy will take decades, with examples from prominent actors expressing this opinion throughout the ESA. For example, as early as 2002, Gasunie predicted that the transition would take another 40 to 50 years. In 2017, at the start of Hyunder, Gasunie emphasized that it would take several decades before gas storage would be balancing the national transmission grid.

4.7.3.1 Projects perpetually take longer than planned

The first consequence of the aforementioned barriers is that projects perpetually take longer than planned. Within the Energy sector ESA for example, the Hystock elektrolyser was expected to start running in Sept 2018, but opened approximately a year later in June 2019. Another example comes in the North-Sea developments, where a first practical experiment at sea was planned at the end of 2019, but this was moved to the end of 2020 – it remains to be seen whether this deadline will be reached. From the mobility sectors' ESA there are also multiple examples of this: (1) Firstly, the I&W grant of 2014 came with the expectation that the 10 busses would be implemented at the end of 2015, but after a start-up period, which was necessary to arrange the public-private coordination between the public transport client, transporter, bus builder, gas station operator, and hydrogen supplier, the first of these buses were deployed in 2017 (October and December). (2) Secondly, the buses that Hermes took over from GVB, that drove in the CUTE project, were supposed to start driving in 2015, but after some delay the two busses were finally deployed in 2017. (3) A third example were the buses that were supposed to start driving in Apeldoorn in 2015; they were finally deployed in 2017, after the small Polish bus supplier Solbus experienced delay due to a large order for Warsaw. (4) Finally, the Pitpoint station in Groningen was supposed to open in June 2019, but technical challenges had delayed the opening by several months.

4.7.3.2 Chicken-egg problem

One major barrier inhibiting the hydrogen niche's progression is the so-called chicken-egg problem, referring to a lack of both supply and demand, which re-enforce each other due to the lack of the other. For example, in mobility there is a lack of hydrogen vehicles (demand), due to a lack of hydrogen filling stations (supply), while there is no incentive for investment in filling stations (supply) due to the bad business case stemming from a lack of vehicles (demand). Throughout the ESA it can be seen that actors actively try to counteract this barrier. Within the energy sector ESA for example, the Hystock (1 MW) electrolyser was an attempt to create supply with the hope that demand would follow accordingly. Within the mobility sector ESA there are also multiple examples of this. The implementation of the first public filling station in Rhoon (2014) was done with the ambition of facilitating more demand; due to the lack of demand at the time, the station had no timeline in which it would have to be lucrative. Furthermore, in 2017 In 2017, the municipality of Arnhem tried to actively attract more hydrogen cars for demand bundling in the context of the European H2Nodes project, since it turned out to be challenging to get more supply. Finally, still in 2019 H2Drive which provided financial support for driving a hydrogen car; because there were still too few hydrogen filling stations, people did not want to invest in hydrogen cars and vice versa, no filling stations were added, because hardly anyone in the Netherlands had a hydrogen car (177 according to the latest figures at the end of 2019).

4.7.3.3 Lacking infrastructure

Mainly as a consequence of the financial barriers and enforced by the chicken-egg problem the final barrier arises. As can be seen from the mobility ESA, the construction of a national network for hydrogen filling stations is crucial for the breakthrough of hydrogen as an energy carrier for cleaner transport. This is also acknowledged by the European Union, which has started H2Benelux (2018), with the main objective to roll out a Benelux network of hydrogen refueling stations (HRS) along the 'TEN-T' (Trans- European Transport Network) Corridors. In 2019, the Dutch government still had the objective of having 20 operational hydrogen filling stations by 2020. The Netherlands had not yet achieved this goal (in July 2020), and it seemed unlikely to happen by the end of 2020, with only five operational in July 2020. The Dutch government had, for example, already planned to go from 4 to 16 hydrogen filling stations in 2018, but that was also not reached. The latest plans also seem to need for re-evaluation, since projects take longer to be developed. Furthermore, in the energy and industry sectors, the infrastructure is also still lacking. Some parties, including Groningen Seaports and AkzoNobel have been working on a so-called hydrogen 'backbone', which tries to combat this issue.

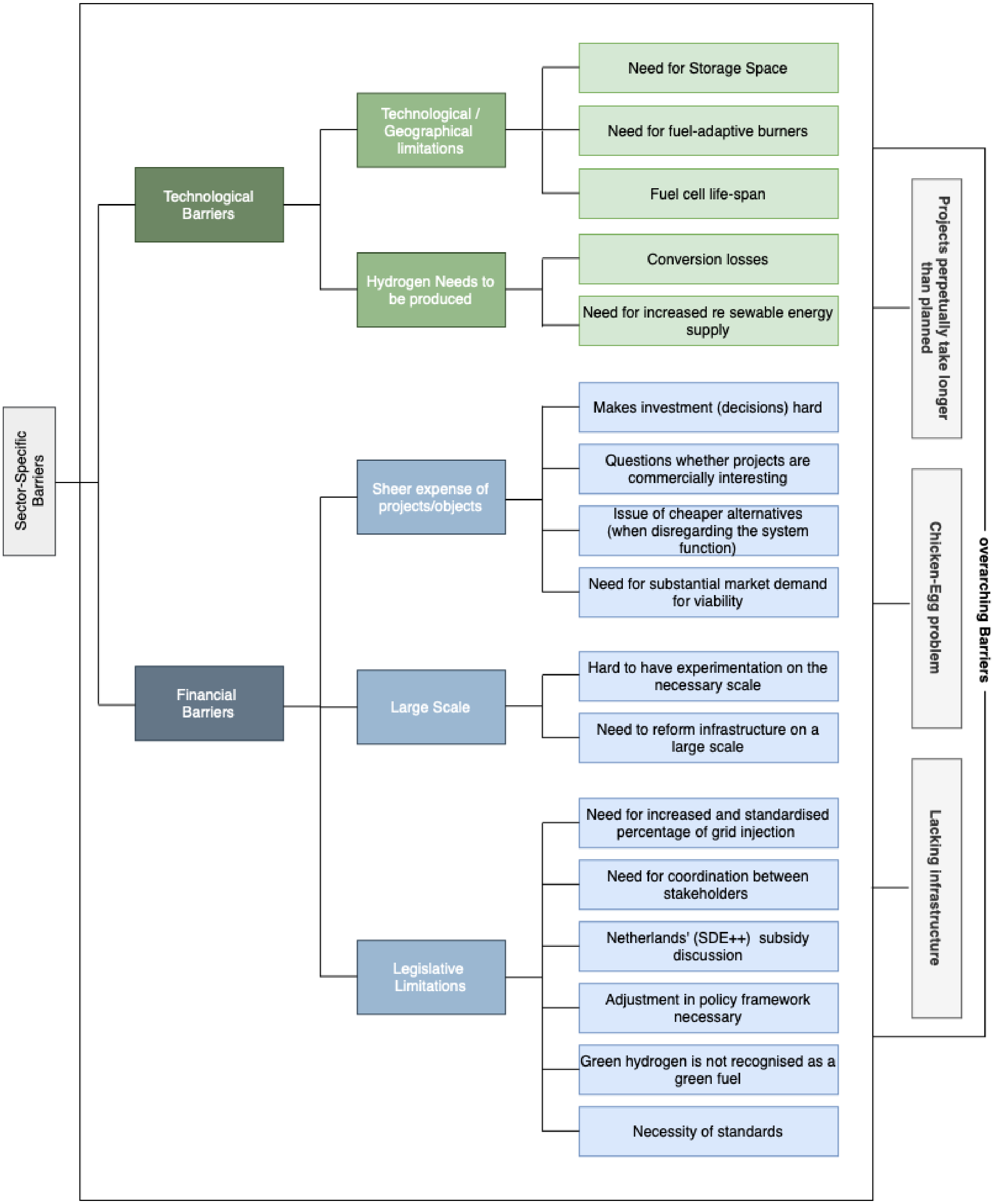

Figure 4.17: Barriers related as uncovered by the Event Sequence Analysis of all corresponding sectors

Chapter 5

Strategic Niche Management Analysis of the Transition Pathway of Hydrogen in the Netherlands

Blue and especially Green Hydrogen in the industry, energy, and mobility sectors are currently mostly in the technological niche phase – only concerning hydrogen buses and cars, there are some instances of market niches. The costs are quite high, and there is a high amount of niche protection, in the form of funding and test projects. Industrial, energy, and mobility parties choose to develop the technology predominantly due to a high landscape and regime destabilizing pressure from the climate movement and high expectations for the molecule's system function due to its advantages compared to other technologies and fuels. Generally, the ESA and interviews showed that the (1) high cost, (2) pending governmental legislation, and (3) funding are considered to be main obstacles for the growth of the niche. This chapter will analyze the underlying factors that can be seen in the hydrogen transition in the Netherlands that are promoting or hindering sector upscaling by first analyzing the dynamics and growth factors from outside the niche and then analyzing factors from within the niche by mainly analyzing the three internal niche processes with the Strategic Niche Management approach.

Section 5.1 will more closely examine the relevant factors and dynamics from outside the niche that influence the sectors. As explained in Chapter 2, the niche can be influenced by the upper MLP levels (regime and landscape) in two ways. First, a destabilized or non-present regime offers windows of opportunity for niche breakthrough. Second, the landscape and regime developments can also influence the niche development by directly affecting the niche processes. This section presents both (1) indirect influences - which are the developments in the regime and resulting possibilities for alignment with the niche – and (2) direct influences - The upper MLP levels influence the niche processes and activities in various direct ways. The bottom-up niche forces can influence upper MLP levels in theory (see Chapter 2), such influences have sporadically been found in the ESA and were mostly described in the previous sections. Even though the hydrogen niche in the Netherlands is still in a very early stage, the high urgency of the energy transition and the good performance of niche internal processes, especially the voicing of expectations, though success stories, have caused such bottom-up influences. Alignment is causing the niche to gain momentum, yet this is not enough, due to (regime) barriers.

5.1 Dynamics and growth factors from outside the Dutch Hydrogen niches

As described in Section 4.1, the climate movement has had tremendous influence on the assertion of pressure on the (fossil-fuel) regime and especially towards promotion of hydrogen from the top-down. As identified by the ESA there were two streams of events that asserted most direct influence on the implementation of hydrogen at the start of the 21^{st} century. Firstly, the September 11, 2001 attacks in the US caused a wave movement towards hydrogen due to its potential to replace oil (and decrease dependence on OPEC). This was simultaneously in-line with the climate movement, which was already going on at the time (in a very early stage), due to the potential for climate neutrality of the energy carrier (hydrogen). The Netherlands has lagged in the Energy Transition, causing the country to be mainly reliant on fossil fuels. This fraction is larger in the industry sector, where the majority of energy comes from fossil fuels. Especially the use of (grey) hydrogen, which is significant in the Dutch industry, is primarily produced from fossil sources. This overreliance exerts considerable pressure on the environment, climate and population.

In every level of the Dutch society, there is still an over-reliance on fossil fuels; the whole energy system consists of only 6% renewable energy, industrial processes are still primarily fossil-based, fossil-fuel vehicles still dominate and domestic heating is still done through natural gas. As part of the European Union, which has ambitious goals for 2030 (55% less emissions), there is an added pressure on the regime to reform. This lagging behind, in addition to an international climate movement (Paris Climate agreement) is the main cause of the Netherlands' shift towards (modern) renewable energy sources. This added pressure, combined with the Netherlands' abundant access to energy and heat, mainly attributed to an electricity grid and natural gas grid that extends across the entire country, made a top-down opening for hydrogen experimentation. This was paired with the fact that the Netherlands was already the 2nd largest producer of (grey) hydrogen in Europe, in addition to its great (import and export) infrastructure.

Especially, after the energy agreement in 2013, it was clear that the energy supply in the Netherlands should change significantly until 2030. Even realistic scenarios for CO_2 reduction and renewable energy already predicted major shifts. This created an opening for fossil-fuel alternatives, in which Wind and Solar energy were mainly looked at for energy production and biomass and hydrogen as energy carriers; they would be used as much as possible in transport, electricity and heat generation. In addition to being an energy carrier, hydrogen was also looked at as a storage medium for electricity in the long term, with a short-term focus, mainly on focus on industry. The Climate movement had several destabilizing pressures on the predominant energy sources (natural gas (40%), oil (39%) and coal (14%)). Namely, in 2014, Oil prices were rising and the share of natural gas that was extracted in Northern Netherlands was announced to be closed in the near future. The same counted for old coal power-plants (such as Hemweg 8), which was ultimately closed in 2019.

The climate movement had sparked several other developments that were of great influence on the hydrogen transition as well. (1) Firstly, the Netherland's position next to the North-Sea has led them to put an explicit focus on offshore wind energy. This parallel niche development paired greatly with green hydrogen, due to the potential of storing landed excess renewable energy (in industrial clusters) through electrolysis. (2) Secondly, this internal regime pressure has led the government to mandate the closure of several (old) coal power-plants and – arguably adding more pressure – by expressing an end-date for the barring of natural gas extraction in Northern-Netherlands (Dutch: Gaskraan), which only seems to be moved closer to the present by new governmental intervention. The Northern-Netherlands cluster was already undergoing its movement towards the hydrogen niche, due to their higher reliance on and expertise with (natural) gas. This added top-down pressure only nudged them more towards the niche. (3) Thirdly the climate movement mandated the reduction of CO_2 emission, which led to more short-term (parallel niche) solutions being sought; most notably in CCS, which created an opening for blue hydrogen. (4) Fourthly, gas power-plants were under-performing due to the climate movement, which caused companies to look for solution, of which hydrogen was at the forefront. The (5) fifth and final development was the observation (backed by research) that keeping the natural gas infrastructure in place, and filling it with alternative gases, would lead to EUR billions of savings on a European level.

The government plays an additional important role in the regime and in the creation of opportunities for hydrogen up-scaling. They have also signaled quite positively about hydrogen explicitly over the years. Nevertheless, there is still an on-going debate about the SDE++ subsidies and whether CCS (for blue hydrogen) and electrolysis (for green hydrogen) will receive sufficient funding, with industrial parties and the government having opposing views. The government sees three main issues with CCS: (1) Applications for CCS would be in competition e.g. solar and geothermal energy, which could lead to it squeezing out renewable energy in the subsidy round. (2) Substantial energy demand of the CCS process itself. (3) Emissions from extraction and transport. Because of these considerations, just as with biomass, the government had set sustainability requirements as a condition for CCS subsidy and only used CCS techniques with full capture as the standard. This discussion around SDE++ about hydrogen and CCS are stabilizing the regime to a certain extent. However, in 2020, the government had developed a plan where hydrogen upscaling received a prominent role.

The conclusion is that the Netherlands' energy, industry and mobility regimes create both opportunities and barriers for the development of green hydrogen. Nevertheless, the opportunities have far outweighed the barriers, with the only major barriers being inherent to the niche itself. These could be overcome mostly through improved internal niche processes (mainly better voicing of expectations on the part of the government) and improving some regime barriers (mixing of natural gas, responsibility for distribution). Up-scaling of the technology has the best chances of success when all relevant actors make a choice to go all-in.

5.2 Dynamics and growth factors within the Dutch Hydrogen niches

5.2.1 The Voicing and Shaping of Expectations

Throughout the development, it can be seen that expectations among actors have aligned quite drastically towards a consensus that hydrogen is necessary for all of the sectors; only within the built environment, there is still the most debate about its necessity, compared to (cheaper) alternatives. These expectations have been influenced by a wide range of factors, from regime and landscape destabilizing developments to learning processes within the niche that have brought more actors in and have shaped expectations positively.

5.2.1.1 Exonogous expectations

Among the exogenous developments, which are developments outside the niche, there have been many influential factors. Primarily after expectations towards hydrogen grew due to Landscape destabilizing pressure from the climate movement, due to a necessary increase in renewable energy, which put more emphasis on storage, for which hydrogen was seen as having much potential, and a push from the Dutch government towards CCS to reach the climate goals, which open windows of opportunity for blue hydrogen. Furthermore, the increasing number of sustainable sources and fewer traditional power plants, meant that there was a need for alternative control capacity. By having electrolyzers take off more or less power, they could be used to stabilize or balance grid stabilization which opened up opportunities for investors in hydrogen production. Throughout the ESA, especially in the industry sector ESA actors like ECN, Nuon, Shell and Essent have directly been attracted towards participating in the niche due to the exogenous developments.

Due to the landscape destabilizing pressures and regime internal tensions that had particularly simultaneous influences on industrial actors and energy sector actors, their motivations and expectations when moving towards hydrogen implementation were very similar. This led to actors partnering on projects and developing plans, which were mutually beneficial to both sectors and the hydrogen transition. An example of such mutually influential developments are the regime destabilizing events around 2007; as a consequence of voicing of positive expectations towards the CCS niche by the government that took office in 2007, in 2008, Essent and Shell envisaged jointly building a new power plant that would run on gasification technology with pre-combustion CCS.

Within the Energy sector ESA, the Landscape destabilizing pressure from the climate movement has been particularly influential on the Northern Netherlands' economy, due to their dependence on gas. This has led them to reorient in a quite early stage towards hydrogen and attract funding from the Netherlands and Europe, further increasing actors that wanted to be involved. Because of this, in North-Netherlands, the first hydrogen-specific events emerged in 2005, while this only happens around 2015 in Rotterdam. Later on, the cluster had positioned itself to become the European hydrogen hub.

In general, the Netherlands' inhabitants and companies were aware of the developments and pushed for governmental interventions quite early on, with examples reaching back to 2002 (Gasunie, 2002). In general, the energy carrier has grown in popularity mainly due to Landscape destabilizing pressures which started with the Kyoto agreement and afterward the Paris Climate agreement (climate movement) showing that the influx of renewable energy would not be sufficient. Furthermore, the offshore wind potential was a parallel niche development that has had significant influence in nudging the Dutch energy regime towards green hydrogen due to the compatibility between the niches. Finally, the debate about CCS is still ongoing. Within industrial parties, there seems to be a consensus that CCS should be seen as a positive and a key to the success of the transition from grey to blue to green hydrogen. However, the limited support from SDE++ signals that the government, even though it sees this as essential as well, sees a lesser role for this development, due to drawbacks associated with the technology and its competitive nature from a subsidy perspective with investments in renewable energy (CUTE, 2008).

5.2.1.2 Endogenous expectations

Among endogenous developments, which are developments within the niche, the feasibility studies and pilots were critical factors in providing positive expectations. Throughout the ESA, research consistently showed that both blue and green hydrogen was technically possible, and climate research showed that the hydrogen niche would be key in the transition towards climate neutrality in 2050. A plethora of industrial, energy sector, and mobility sector actors expressed this positive expectation, as well as the Dutch government. Especially the mobility sector has had a number of 'success stories' reaching back to the early 2000s, starting with the CUTE project in 2003. There was also alignment in expectations that the development should be on a system level for all different sectors, which would mean that the transition would take decades. This was once again re-enforced by experimentation. Most projects were still not yet cost-competitive and therefore still in a technological niche phase; after decades of optimization hydrogen buses were still too expensive and green hydrogen is three times more expensive than grey hydrogen (CE Delft, 2018).

In industry and the energy sector studies were a key focus in the early 2000s until around 2015. This helped the expectation that hydrogen would be a success, with a focus on blue hydrogen to create learning processes and a significant enough market, in order for the cost of electrolysis to decrease to become competitive and green hydrogen to become cheap enough. Additionally, substantial subsidies from the EC and the Dutch Government - even though there is debate about whether it has been enough - and the presence of multiple planned projects promote a positive attitude towards the hydrogen transition. In the mobility sector, European involvement was deemed essential, especially after 2013. The learning process that large-scale infrastructure and a plethora of tests was pivotal drove the EU to initiate larger scale projects (with Dutch involvement) and grant subsidies towards Dutch practical experiments. These projects had a clear goal of learning to improve the niche's further implementation - which was moving forward due to the positive expectations from actors from all sectors, and the EU and Dutch government alike.

Learning has had a tremendous influence on actors' expectations within the niche, but especially for actors outside the niche (and to attract new actors). For the two decades after 2000, learning has perpetually caused alignment in expectations, multiple independent studies gave the same results, showing technical feasibility and high potential for hydrogen. These learning experiences have altered and aligned expectations on the necessity of hydrogen in a Dutch energy transition and laid bare the key barriers that are in place. This has, in turn, led to alignment among actors on how the transition should be tackled. These positive expectations (in addition to Landscape and Regime destabilizing shifts) have attracted more actors to interact with the niche and has promoted Network building with actors forming large cooperatives (e.g., h-Vision) and partnerships (e.g., Gasunie and Tennet or AkzoNobel, Pitpoint and Groningen Seaports) that span over multiple projects across years.

To conclude, internally, there is quite some alignment when it comes to expectations of hydrogen. However, the fact that there are many project plans, but not a lot of definite decision, makes it that only time will tell whether these projects will come to fruition. Also, the debate about CCS affects blue hydrogen projects like h-Vision, causing some doubts about the future of hydrogen. One significant discussion is that of different stakeholders; Since the government has not made clear who is responsible for the distribution, there is a hesitation for public and private parties alike to invest. These decisions should be made soon in order to improve the quality of expectations. Internal Expectations.

5.2.1.3 Internal Expectations

Regarding the expectations of the niche actors themselves, the internal expectations are similar among the actors. Whereas some are getting increasingly involved and starting up pilots or partnerships due to regime influences, others have gained favorable expectations due to positive outcomes of hydrogen projects or feasibility studies. Studies from TNO and CE Delft, which promoted hydrogen as essential for the energy transition and a need for regime reform were especially influential. For the most part, expectations are also aligned on the viability of the niche in terms of technical implementation, and there is overlap between different projects regarding the most suitable business strategy or the partnerships that are necessary to realize upscaling. There is also consensus regarding impact that electrolysis can have on the refinery, chemical and steel industries. Another shared expectation is that there is not enough renewable energy potential in the Netherlands to fulfill its full hydrogen energy needs, which means that import will stay a significant factor for the country.

There are still some aspects where research is necessary when it comes to the percentage of mixing hydrogen with natural gas and the importance that the government should place on this. Furthermore, As already mentioned, there is still a debate about the subsidy that the Netherlands should give towards Blue and green hydrogen. This is also an aspect that underwent a lot of learning processes and showed excellent adaptive qualities. At first, electrolysis was not considered for SDE++ at all, and the subsidies for blue hydrogen were quite low. This caused industrial parties to ban together (due to aligned expectations) to ask for a revision. This has been done, and subsidy for blue hydrogen has increased, showing that the government is backing hydrogen as well (even though the amount might still be too low). Hence, the expectations are quite specific but can use some improvements to increase specificity and attract more parties to get involved with the niche.

Concerning the internal expectations, they are quite aligned. This does not necessarily mean that the expectations are overwhelmingly positive, but most actors express the same concerns. Learning processes are universal and are taken into consideration carefully. Most actors have increased efforts due to positive regime influences and gained positive expectations from successful projects and learning processes that have shown high potential in the North-Netherlands area. Multiple actors expressed similar statements about the positive expectations of hydrogen's system function and the fact that there is tremendous market potential (but still hard to reach the market due to competitive niches). Another shared expectation entails the lack of technical challenges with the niche. Finally, there are some areas where expectations can be aligned more, for example, when it comes to the percentage of mixing in the grid. Also, with specificity, there are still strides to be made when it comes to ideal design. This is something that actors also express and work towards actively. Actors expressed multiple times that experiments are specifically meant for all different types of learning. There are overwhelming shared expectations regarding (1) the necessity to decrease cost and (2) the positive impact that hydrogen can have.

5.2.1.4 External Expectations

With the external expectations, the awareness and perception of actors outside the niche are evaluated. The Dutch public is generally in favor of renewable energy, and there is a realization in the past couple of years that a system transformation with hydrogen is necessary. Mostly, as a result of governmental backing of the niche and devoted documentaries, like the show 'tegenlicht' (from VPRO), first with a focus on hydrogen in mobility in 2004 and then a focus on hydrogen's system function in 2017. Additionally, from around 2013 onwards, there has been a significant increase in news items on the subject, which again increased in 2017, which is a reflection on the number of new projects as well as an increase in reporting. This increase in reporting can be attributed to an increase in public awareness and interest.

While there was still also some negativity attributed to the risk factor of the molecule among the public, these concerns have become minimal in recent years due to learning processes, overwhelmingly positive expectations from experts, and a lack of accidents in recent history. Additionally, there is also some skepticism regarding CCS among the public, which comes from two main reasons: (1) risk factor due to the possibility of explosion and (2) it not being fully sustainable. The first criticism is counteracted by plans with storage under the seabed (and not on land close to neighborhoods). The second criticism still lingers, and the debate continues. The government is also still not decided or has not expressed clearly which 'side' it is on. When it comes to the government, they have shown substantial support for the niche and have active involvement in subsidizing projects. Additionally, their dialogue with industrial actors and the hydrogen roadmap (published in march 2020) gives excellent support to the sector and shows that it has very positive expectations. As mentioned, there are still ambiguities and aspects where opinions differ between government and industrial parties, such as SDE++ (for green and blue) and decision-making about the person responsible for distribution and how much can be mixed and whether that offers financial benefits for companies. These ambiguities do prevent developments, and this hinders the desire of technology suppliers and other supporting actors to join the niche.

Aside from these criticisms, generally speaking, the external expectations towards hydrogen are quite positive, due to the potential solution on different aspects, from the gas-dependent economy to gas-related earthquakes that would be solved with one all-encompassing solution. Furthermore, the negative expectations have not hindered the desire of market parties and technology suppliers, the government and other supporting actors to join the niche, due to the considerable potential and hype around the niche. Financial investors have also seemed to be interested in investing, despite the market not being proven yet. So, the external expectations, although still various, are of high quality. Nevertheless, to reach full potential, there is still a need to voice and stimulate positive expectations by delivering high-quality goods and services and awareness creation. Furthermore, among external actors, there is still uncertainty about whether projects will be executed (and not only remain plans) due to the sheer size, funding needed, and history of plans that have not been followed through, in industry. This extends towards mobility projects; in 2020, 20 tank stations should have been realized, but there are still only 5. Because of this, stakeholders state that "it remains 'first seeing, then believing', because previously both Gasunie and Shell have presented plans of which nothing has been realized yet".

To conclude, the external expectations are the most diverse from the other three expectation types but still shows quite some alignment. This can be overcome through continued interaction between the government and industrial parties, which can then voice and stimulate positive expectations to the general public (if it is deserved – if more alignment is reached).

5.2.1.5 Quality of voicing and Shaping of Expectations

In the Netherlands, expectations have given direction to the development of hydrogen, and have influenced design choices, attracted resources as well as new actors. There have been a number of 'success stories,' especially in terms of research projects and research reports that have made expectations towards hydrogen converge. Since blue and green hydrogen are both still developing and unproven, these positive expectations have been pivotal in moving the development of the niche forward and getting the right actors involved to perform experiments properly. One main issue is that there is not a lot of practical experimentation yet, and there are mainly short-term and small-scale results, which may not be representative of longer-term conditions. One back-up for the Netherlands is that, in the industry sector, there is already a significant market share that uses hydrogen, so this is already backed by evidence. However, for the rest of the sectors and the rest of the supply chain (production and distribution & storage), there is still much experimentation to be done, before expectations can be backed by sufficient evidence. Nevertheless, there has been a focus on gathering results from experimentation and implementing this in future development, even though this has still been on a short-term and small scale. This lack of large-scale experimentation largely attributed to the sheer scale of the transition and is only not a consequence of actors' inabilities or lack of effort.

The (mostly) positive expectations of hydrogen's system function have had a major impact on the direction that hydrogen development has taken over the years, since in this early stage, actors have thus mainly joined the niche because they have expectations of future success. During the development, expectations have changed due to external factors (regime and landscape) and internal circumstances (e.g., results from experiments within the niche) as well as internal and external developments. When seen in the light of van der Laak et al.'s (2007) conditions for high-quality expectations formation, the performance of this niche process is quite aligned, with still opposing expectations from a minority. This alignment stems from the fact that actors properly share expectations (alignment) (TU Delft, 2005; ECN, 2015; DNV GL, 2015; DNV GL, 2019; Shell, 2017). Over time, expectations have been shared by more actors (more Robust) and they have become more focused and have given guidance to the niche transition (clear and specific). For example, the The EU's involvement and focus on hydrogen have made companies focus on implementing hydrogen buses instead of a scattered focus between EVs and hydrogen. Expectations have been validated from on-going experiments and backed by sufficient evidence (Higher quality). Examples of this can be found all throughout the ESA; for example, the implementation of the first filling station (in Rhoon) showed that more plans were starting up and showed that filling up would only take a couple of minutes. Furthermore, research also showed that the risk of flammability was not an issue, which has been validated by research and the observation that there have been minimal accidents in the last 20 years of experimenting. Finally, research reports that published expectations that were aligned with the consensus of the majority of actors and have caused new key actors to join the network, which has guided experimentation (h-Vision and CE-Delft, 2018).

Overall the voicing of expectations is quite positive from an SNM perspective. Throughout the entire development, the SNM feedback loop is tangibly visible; actors express positive expectations or actively seek learning processes, which in turn causes the network to grow. Expectations of industrial parties are highly specific and based on tangible results from experiments (Statoil, 2016; AkzoNobel, 2017; Statoil, 2017; h-Vision, 2017). There seems to be a consensus about the future of the niche and how this should be reached (seen by the fact that they banded together to write a petition to minister Wiebes when they though funding was not sufficient) (CE-Delft, 2018; h-Vision, 2018; ECN, 2017). The government has had multiple instances of signaling that it has mildly positive expectations regarding the niche. Nevertheless, there is still a significant step that has to be taken in this regard; the government needs to specify its expectations, and tangible steps should be taken when it comes to subsidy and regulations since market parties are highly dependent on the position that the government takes. This is currently causing market parties (especially in distribution) not to interact and join niche experiments, as well as causing some projects to potentially not coming to fruition due to lack of funding.

5.2.2 Network Building

When it comes to network building, the literature shows that one main criteria is that the network should involve all relevant actors (completeness) so that the ideal composition and the required actor composition and linkages is reached in order to reach successful niche upscaling – as well as it being pivotal that there is a broad network that the network is broad. Although more research is necessary to evaluate what the ideal hydrogen network is for the Netherlands specifically to reach upscaling, through the ESA much can be said about the involvement of a broader range of actors over time and the nature of the interactions between these actors. Furthermore, the ESA has shown the degree to which actors' vision, expectations and strategies are in line with the niche development. With this background, the following paragraphs will discuss the network building that has taken place, particularly between 2000 and 2020.

5.2.2.1 Network composition

As explained in section 5.2; in order to reach proper hydrogen (economy) upscaling, there need to be actors from different sectors from all levels of the supply chain for two different types of hydrogen (blue and green) that have to offer hydrogen with different levels of pureness to different types of user groups in four different sectors. For a lack of further research into the ideal network composition, there are 'obvious' actors such as hydrogen suppliers, the national government, the European Union, supply chain, research institutes, umbrella organizations (consortia) and other 'less obvious' actors like local authorities (provinces or cities) - because they influence product perception and give permits for (and promote) development projects - and financial institutions (like the Waddenfonds) - because they can support end-users with funding.

When evaluating building of the actor network that has emerged from 20 years of blue and green hydrogen niche development, it can be seen that virtually all significant actor groups (previously mentioned) have been included, mainly due to the high expectations and learning processes related to the technology. Strategic partnerships have been formed in all facets of the development; e.g. in Groningen, the partnership from Groningen Seaports and Nouryon was a strategic one that was based on learning processes from both companies individually, as well as collective learning of the necessity for the future. Nouryon had years of experience with the production of grey hydrogen and Groningen Seaports had years of experience with distribution, hence the partnership was strategic to make use of strengths of both companies. From an early stage, different consortia were formed with all different types of actors, from producers, distributors, research institutes, universities, users, etc. For example, TNO worked together with TU Delft from 2004 onwards, implementing new learning processes in subsequent projects. These learning processes are then taken to follow-up consortia, where both actors individually participate. Another example came in 2014 in the mobility sector, when VDL implemented the same hydrogen buses from the CUTE project in Eindhoven, which meant that the learning processes could be shared, and the experiment could be set up properly (lateral interaction).

Over the years, multiple different actors from different sectors were attracted to the niche development, due to the voicing of expectations or the active seeking for strategic partnerships. Importantly – as can be seen in Figure 5.1, which shows lateral links between stakeholders in different projects -, multiple actors work together in different projects spanning a plethora of years or even decades. This is important, since the actors take their learning processes and implement them actively in follow-up projects, as well as projects that are done abroad and vice versa. Additionally, these actors form multiple partnerships with different actor groups, which means that they can share their knowledge and expertise across a large group of actors. As can be seen from the ESA descriptions, the government actively engages in conversation with industrial parties. The EU as well as Dutch government are actively involved and have invested in highly influential projects (e.g. Hyunder). Furthermore, local authorities are included in such projects or set-up their own projects (e.g. Energy Valley). Financial institutions, like Waddenfonds, play an active role in facilitating projects. Finally, crucial partnerships have been formed, which influence the transition pathway positively, most notably the partnership between Gasunie and Tennet, which was a consequence of the first 1MW elektolyser pilot in Northern-Netherlands.

The companies that are investing most in the Netherlands' industry sector are big Dutch multinationals, including Akzonobel and Shell as well as Dutch industrial companies such as Groningen Seaports and Gasunie. Hence there appears to be a high interest from local companies. Additionally, Dutch Universities and research institutes, like TU Delft and TNO respectively, are also very much involved in development of reactors and technology as well as doing research on different topic like technology, business plan and infrastructure. So, the development in industry seems to be predominantly led by Dutch actors, even though international knowledge, predominantly from European projects, to a lesser extent also have influence. This can be attributed to the Netherlands' history with research, development and experience, especially with gas infrastructure and export and import. Therefor they are at the forefront of development and can grant an active contribution towards these developments globally as well as locally.

The current industrial hydrogen network consists of companies that already have experience with grey hydrogen (e.g., AkzoNobel) that recognize the necessity and opportunities for hydrogen's system function and also see the necessity of investing in this transition as soon as possible. For the energy sector, the main companies investing are already-established Dutch utilities, including Gasunie, Tennet and Stedin. For the Mobility sector, also Dutch transport carriers invested heavily (RET, Conexxion, Hermes). Both these sectors were more highly dependent on European Union investments. This European dependence can be attributed to the realization that the costs are very high and European funding, as well as learning synergies are essential for the niche to become successful. This network building is most notably seen in Northern-Netherlands where the right institutions all have come together over the past 20 years (2000 – 2020), which has led the European government to pronounce the area as hydrogen hub of Europe with the biggest grant given to date.

Even though most actor groups are included, some network building has been very recent and should have started earlier, which has a lot to do with uncertainty regarding the development and responsibilities; only recently, in the period 2017 – 2019, the important partnership between TenneT and Gasunie was formed. Due to the lackluster market currently, the involvement of users in different sectors is especially problematic, and TSOs and DSOs are still not involved enough, which has led to an absence of experimentation of the distribution and service network.

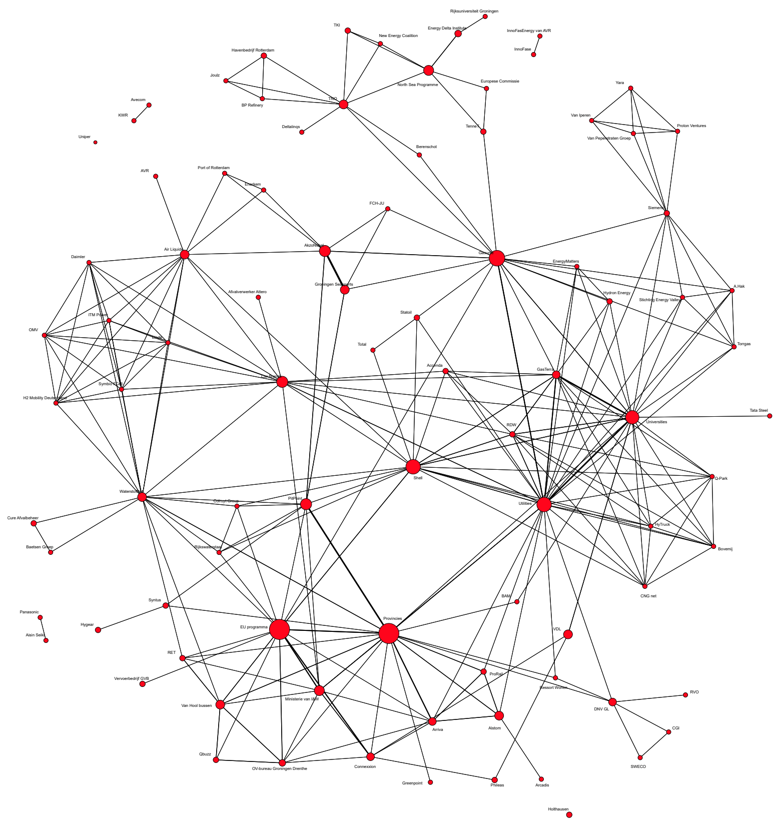

Figure 5.1: **Network plot**: This network plot has been created by coding all of the involved parties in all relevant hydrogen events in the Netherlands between 2000 and 2020. It shows to which degree stakeholders have worked together across different projects in that period. The thickness of the lines indicates how often certain stakeholders have worked together and the size of the red circles indicate how often the stakeholders have worked on a project related to hydrogen.

5.2.2.2 Network Interactions

According to the literature, the network should not only be complete, the intensity of participation and quality of performance of its individual actor groups are as important as its actual composition.

Individual parties have been identified to have performed properly, which led to successful outcome of projects, such as AkzoNobel, Pitpoint and Groningen seaports having worked together in a manner that production, distribution and use all came together to fulfill the project. Furthermore, in a follow-up to this same project, the parties have attracted the appropriate actors (four actors), to fulfil all aspects of the supply chain. Furthermore, Individual actors seem to possess enough expertise, therefor actors are able to produce high quality projects, despite the many difficulties they experience in this process, including (1) the immense expertise needed in this field, (2) a need for knowledgeable employees and (3) a need for different materials. Nevertheless, there has not been much practical experimentation, so this should be re-evaluated.

Generally, from 2000 onwards there are multiple linkages between the different Dutch hydrogen actors from up and down the supply chain, which has led to substantial common knowledge on the hydrogen technology and user experiences. Almost every time a new actor initiated a hydrogen experiment, the actor started from a point where either its own previous learning experiences has been taken into account or they have built upon gained experiences of partners. These partnerships have been formed, firstly due to the sheer complexity of the development of this niche and the different expertise of actors. They could link up due to the clear communication outwards of most actors, therefore most projects are known to all actors. Furthermore, there have been no known cases of resistant attitude of actors to cooperate and share learning experiences. The culture seems to be one in which companies believe that partnerships are only positive, for which Gasunie and AkzoNobel were both in alignment.

Finally, the abundance of network interactions can also be seen by the substantial consortia which have been formed over the years (h-Vision, WaterstofNet, H2ME). This is enhanced by the general expectations which multiple actors have expressed, namely that in order to have a successful hydrogen economy, the whole supply chain from all sectors should be involved. This, in combination with the stability of the network causes the niche's high network alignment. Yet, due to a lack of regulatory alignment, some actors – mainly from distribution networks - have not yet (or only very recently) become involved in the network. In conclusion, even though some necessary actors in the network are still missing, the majority of the important actors are involved and have been for years, have had meaningful interactions over the years, which has led to significant alignment within the niche. Therefore, important linkages between actors have been accomplished, which only need to be further broadened and strengthened. However, there is a lack of practical experiments, which limits the evaluation that can be made on network building.

5.2.2.3 Quality of Network Building

When taking in to account van der Laak's (2007) criteria for a highly-functioning network, the network mostly complies with the two criteria; from the ESA, it becomes clear that the actor types have broadened over the years, while alignment between them has increased. the network participants consistently reported evidence of continued expansion and increasing network variety. It can be seen that with every new event, more and diverse actors joined the niche, with partnerships being formed in a manner that they enhance each other's shortcomings (Highly functioning). Nevertheless, it has not been optimal for the full expanse of the ESA. As can be seen in the first calculations by PBL for the SDE++, if there was better mutual interaction between them and industrial parties, the backlash could have been avoided, and expectations could have been improved. This led the government to have to revise the whole subsidy scheme, which has caused quite some commotion and extra time that could have been spent on further developing the hydrogen goals. Finally, the niche's positive expectations have also attracted network building, most notably with AkzoNobel, Groningen Seaports, and Gasunie working together to build a hydrogen "Backbone" in North-Netherlands. The collaboration between AkzoNobel and Gasunie, therefore, brought together the necessary expertise in the field of gas transport and storage, electrolysis, and handling hydrogen. Both parties considered it essential to play an active role in the transition to a CO_2 neutral economy.

The experiments among all sectors are also connected to some extent through what one could call 'bridging organizations', which means that some of the organizations that have taken place in a previous experiment also are involved in the next, which brings with it the learning processes and expertise. Due to the excellent reporting on findings of experiments, uninvolved parties in projects across regions and clusters can use these learning processes and report that they do so, thus the interexperiment network is tight and unified. These actor networks have attracted resources, and new actors enabled learning and carried expectations. Therefore, in the Netherlands' hydrogen niche, the actor Network has become quite broad (These include the government, municipalities, bus manufacturers (national - VDL, HyMove - and international - Solbus), Filling station manufacturers (Air Liquide, Pitpoint), transport carriers (RET, Connexxxion, Hermes), universities (TU Delft, TU Eindhoven, Hanze Hogeschool), and interaction between these actors was plentiful. This frequent contact, in turn, increased alignment between actors and thus increased the niche's potential. Additionally, actors from different sectors have also formed partnerships, such as in the case of a partnership between Pitpoint, AkzoNobel and Groningen Seaports. The alignment between actors can be seen through the cooperation between the different projects in a plethora of experiments. The network can be considered highly-functioning since it generated coordination and convergence between varying expectations (more on this in the analysis of the expectations).

5.2.3 Learning Process

Although some experiments have been conducted before the 21^{st} century, it was after 2001 that landscape influences started to put destabilizing pressure on the regime, together with a backing from the European Union, after which European parties started experimenting and actively learn about the niche.

The ESA shows that the learning experiences from around 17 years (2003-2020) are very coherent, partly due to the linkages between the actors mentioned in Section 5.1.2. When there was no such linkage, previous studies were consulted and conclusions were in line with each other, leading to further alignment in expectations (For example in the Hoogeveen built environment experiment (2018), Stedin's Ameland experiment (2008 – 2012) was mentioned extensively). Furthermore, the ESA shows that various actors have specifically focused on learning, whether through specific feasibility studies, general research or experiments, tests and pilots where the primary goal was stated to be for 'learning'. This is the case for multiple independent events, from multiple stakeholders and actors, expressing the same desire for and emphasis on learning.

In the Netherland there were a couple of instances with second-order learning. Most of this second-order learning took place by independent research institutes, including ECN (TNO) and CE Delft, but also by market actors that had performed feasibility studies in big consortia, like h-Vision, WaterstofNet. Many of these consortia did include the former mentioned research institute TNO. Learning was mainly focused on system impacts (blending), business models and technical impacts. This learning led to important lessons regarding what could be alternative niche markets, the key elements of what an appropriate business model should entail and most importantly on how the niche should be implemented in the future and what financial help was necessary by parties and government. First-order learning came in the form of experiments abroad, for example with Statoil that had experimented with CCS on a large scale or Shell implementing a relatively large electrolyser in Keulen. These parties could share their experience due to the great Network building that had taken place, where they worked together with other actors on pilots and studies in the Netherlands.

The EU has also invested in projects related to learning, for example with Hyunder to learn about storage in North Netherlands (capacity aspects). This has even more recently led to private parties, like Gasunie gaining funding from EU to build the first 1MW elektrolyser in North-Netherlands, which was mainly meant for first-order learning about technical and economic aspects. The lessons in the private sector were valuable, but still quite limited due to the large scale needed, which takes funding and time, and thus still a lack of practical experiments with enough scale. Thus, the private sector was both focused on second-order learning, by working together with independent research institutes and had aspirations to develop first-order learning, about technical and economic aspects by building elektrolysers with an increasing scale. These electrolysers are still market niches with a high level of market protection with only a relatively small one (1.1 MW) realized currently. These decisions would depend on feasibility studies and the amount of funding the European and Dutch governments are opening up to them. It is a good sign that studies are being carried out thoroughly and that the government endorsed the developments with the hydrogen outlook in March 2020. This should only be backed up with funding and concrete regulations - there have been incidents in the past, where the government backed hydrogen, but industrial parties were not satifsfied with the amount of funding provided, which led to them doubting the government's intentions.

5.2.3.1 Technical Learning

Regarding technical aspects of hydrogen implementation, multiple learning processes can be distinguished; there was learning regarding (1) the way to store hydrogen (in salt caverns – Hyunder), (2) technical aspects to do with reformation of the gas infrastructure, (3) the amount of blending with natural gas, (4) the design of a blue hydrogen and green hydrogen plant - in combination with other sectors such as a gas station of gas-to-power. The main conclusion of most of the studies was that both blue and green hydrogen would be technically feasible on every aspect, where research proved that all components are either already available or will be able to develop.

Dutch actors have learned that different purity levels of hydrogen are needed for different applications. Additionally, when it comes to mixing, there is a different optimum point than is permitted in the Dutch energy system. Dutch industrial actors have learnt that in order to have a successful transition, technical improvements have to be made, especially to lower the product price. Learning has therefore often been performed especially with this goal in mind. With regard to blue hydrogen, several actors have experimented with different production types in combination with different CCS types. These learning experiences, are still in a very early stage, which do not conclusively show improvements, in terms of efficiency and cost. In the TNO study (2017) it became clear that it would quickly lead to a CO_2 reduction, even before the feasibility study was completed in 2019, they had already clearly announced this in 2018. The stakeholders were also very certain about technical aspects.

When it comes to practical experiments, the debate regarding subsidies for CCS projects from SDE++ has limited some projects' ability (most notably h-vision) to successfully experiment and test hypotheses from the feasibility studies in a timely manner. This is worrisome, due to the perceived function of blue hydrogen as a transition step towards green hydrogen. Research institutes (CE Delft), multiple private parties (through independent research) and validation interviews have expressed the same expectation; namely that the Netherlands should start immediately with implementing blue hydrogen in order to make the needed efficiency gains, create market and gain technical as well as social learning processes. This expectation extends to the fact the green hydrogen will undergo inevitable cost reduction through technological improvement until around 2030, meaning that until then, the necessary learning processes should be undergone through large-scale blue hydrogen implementation. If this parties wait too long with this, it could possibly be detrimental to the hydrogen transition in the Netherlands.

Finally, due to existing feedback mechanisms between foreign implementations (from e.g. Shell and Statoil), with companies that are involved with projects in the Netherlands or have close communication with them, learning processes can be skipped and taken into account when starting projects in the Netherlands. With contexts not differing much between European states and years of experience with interconnectivity between e.g. Germany and the Netherlands learning processes do not have to be altered drastically.

5.2.3.2 Storage and distribution Learning

There have been valuable learning experiences regarding storage and distribution, due to the Dutch and European government's recent efforts in research towards developing data on storage capacity (mainly in North Netherlands) and private parties technical gaining technical experience with this (EnergyStock). Additionally, funding has been given to develop this further (in addition to developing the 1 MW Hystock elektrolyser), with a focus on storage, distribution and interconnectivity with foreign countries (COBRA cable). Nonetheless, actors, validated by interviewees, stress the need for better institutional support, particularly on clearly assigning responsibility to which parties will be responsible for distribution (private or DSO/TSO or something else), in addition to tax and subsidy arrangements (since currently hydrogen blending is not seen as renewable in the current system, which is hindering companies from getting involved) for suppliers. In this context, a TNO study concluded that many more parties would invest if there was clarity about, which is validated through interviews. This is making parties hesitant to get involved, especially in distribution, which has an impact on learning. As a consequence, another critical aspect appears to be the difficulty to act upon the theoretical lessons learnt about the need for an enhanced distribution network.

Finally, a consensus was reached through studies, that adaptations to the distribution network would not be technically challenging, nevertheless, real experiments have up to this point always proven more difficult than imagined, so until learning processes from practical experiments are undergone, not much more can be stated about this observation.

5.2.3.3 Development of the user context

Because of the lack of buyer–supplier interactions in the industry and energy sectors, due to a market that still needs to grow, knowledge is lacking on how the consumers perceive the technology, the extent to which it fulfills their needs and the impact it has. There is also a need for more intra-sector connectivity, which is also partly due to the sheer infancy of the niche. Households are practically not in the picture for hydrogen on a large scale any time soon and hydrogen cars are still lacking (+/- 200 cars) and only 5 refueling stations. Also, due to learning concerning the need for partnerships, better distribution channels and potential target markets, actors have actively worked on network building to use strengths in partnerships and turn these lessons into viable business models. Even though, due to the infancy, it is still a matter of time whether these business models prove to be practically feasible and lucrative.

From the practical experimentation in the mobility sector, the user-experience for public transport seems to only improve. For drivers, the experience changes slightly; while driving is similar to electric vehicles, filling up the car is akin to that of internal combustion engines. Regarding end-users in industry, for blue hydrogen there are not many learning processes, since the product that will be delivered will be the same. As mentioned above, the main lesson was regarding the different pureness levels needed per sector, which has an effect on the amount of refinement that is necessary. Most of the same industries will be using this as a feedstock (e.g., refineries, chemical industry).

To conclude, lessons have been learnt on many aspects and learning experiences have been in line with one another. A lot of these learning processes are quite recent and still need to be proven in practice (also to gain more first-order learning). Due to the scale of this transition, first-order learning has been limited and learning processes have only recently resulted into practical actions (HyStock) and solutions. Additionally, there have been and are still some issues holding back optimal learning, which need to be addressed soon.

5.2.3.4 Learning process quality

When viewing the learning processes against van der Laak et al.'s (2007) conditions for good-quality learning, this niche process was impressive in terms of breadth (which went well beyond technical issues). Additionally, it was found that actors actively questioned and tested underlying assumptions surrounding hydrogen in all levels of the supply chain ('reflexiveness'), for example, concerning the potential to re-use boring platforms in the North Sea for hydrogen production or the fact that the flammability risk was proven to be minimal (in the CUTE project). For new technologies, it is critical that proper learning processes are in place. The learning was broad, focusing not only on technological and financial optimization, but also on aligning technical with social considerations and impacts. Actors applied "elasticity" by examining the fundamental social values attributed to the technology while applying that as a feedback loop for future technological design. The learning process was properly executed, which led to uncovering appropriate opportunities and barriers for implementing the hydrogen niche.

The niche learning process involved both first- and second-order learning. In projects like Hystock, the Magnum Power-plant, h-Vision and all bus implementations, there is more a focus on learning and optimizing processes based on the accumulation of information on various elements, e.g., on the technical infrastructure, developments within the industry, impact on the environment, and user practices. These projects thus encompassed learning about hydrogen's effectiveness in achieving pre-defined goals and were directed on gathering facts and data. Furthermore, projects like Hyunder challenged the underlying assumptions about the technology, e.g., social values and norms regarding the technology. Furthermore, in the mobility ESA, team FAST was reflexive enough to shift their focus towards a different sector after undergoing learning processes of their formic acid fuel-cell development, which was primarily for transport purposes.In that case, actors showed the flexibility to reevaluate expectations and rebuild the social network. This type of learning enabled changes in assumptions and cognitive frames.

For industry, learning on the user side is not as important as in the other sectors since it is a product that has been used (as a feedstock) for decades. For potential users of hydrogen as an energy carrier, industrial actors usually have experience with similar gasses. Additionally, in Europe, 'success stories,' most notably in Norway, have propelled the niche in the Netherlands due to network building with the company that performed the project abroad (Statoil). Experimentations with blue (Norway) and green hydrogen (most notably in Germany) are pointing in a positive direction, especially about practical applicability and technical feasibility. Although technically there seem not to be any uncertainties anymore, there is still the financial aspect and the fact that the whole system needs to be reformed (and the choice had to be made to be 'stuck' with hydrogen for the foreseeable future) that is causing parties to be skeptical. There is also evidence of questioning of broader assumptions about the technology and its performance, like when the system function got precedence or when it was learned that different applications need different levels of purity.

In conclusion, there has been a focus on all the relevant learning types that have been defined in Section 3.4. There are still some improvements to be made when it comes to learning in terms of Government policy and regulatory framework. For example, the excise duty for hydrogen vehicles seems not to be working correctly, since hydrogen vehicles' adoption has not increased as a consequence. Furthermore, there has not been an effort to figure out the optimal amount of financial help necessary to make the option attractive to potential buyers. Undoubtedly, there are many more factors that have to be taken into account, like the availability of a tank infrastructure and the expectations of users; the more positive, the higher their willingness to pay. These are all learning processes that still have to be actively sought out.

5.2.4 Overall Quality of Internal Niche Processes

Overall, the SNM processes in the analyzed niche have proceeded quite well. Learning processes have been sought out actively, and the involved parties showed the flexibility to shift (expectations and experimentation) if necessary. It is clearly visible that successive experiments take into account the learning processes from previous experiments. Expectations have been aligning over the course of the development, and there has been an active pursuit to back expectations with evidence (Robustness), more specific and of higher quality, which the parties have achieved throughout the experimentation (phase). When it comes to the Network building, a broad range of actor types have participated, and alignment has increased over the years (Highly-functioning). There is still room for improvement in the broadness; for example, research institutes (such as TNO (ECN)) seem to be missing from this sector. In particular, the network needs to develop more lateral relations for more effective and broader experimentation and learning, and for alignment of expectations to occur. Summing up the results for the three niche processes in the energy sector, there has been considerable growth, and dynamism and expectations are increasingly based on evidence. Overall, the niche formation processes seem to be proceeding well for the energy sector.

To conclude, generally, the expectations of industrial actors are positive, but they remain skeptical about the future applicability. This is strengthened by the fact that most plans that have been proposed up to the time of writing (Mid-2020) were still in the planning phase, where an investment decision still had to be made. Historical precedence showed that some projects (e.g., Shell and Essent project in 2008) did not reach the development phase due to the sheer expense. Overall, the industry sector's niche formation processes are (slightly) positive according to all the quality criteria listed by van der Laak, et al. (2007). Learning processes have been very broad, containing first- and second-order learning. These learning processes have shaped actor expectations and reshaped experimentation (in a positive sense).

5.3 Conclusion of the SNM analysis: Internal Niche Barriers

5.3.1 Barriers related to the Voicing of Expectations

Within the Voicing of Expectations internal niche process, a number of barriers have been uncovered, which are explained in Table 6.5 and illustrated in Figure 5.2.

Table 5.1: Expectations-related barriers

Expectation Barrier	**Description**
#1	Misalignment in expectations between external parties (most notably the Government) and industrial actors (internal parties) causes a dwindling of positive expectations, due to unprofitability of blue hydrogen projects. Actors have expressed that it is pivotal that these projects start-up in a timely manner, since there is a consensus among internal parties that the for the transition to be successful, blue hydrogen and green hydrogen should be pursued simultaneously, with an emphasis on immediate practical implementation of blue hydrogen to attract more demand and create the necessary infrastructure which will inevitably be necessary for green hydrogen. Even though the government has signaled positive expectations towards hydrogen's system function throughout the ESA and especially in recent years, they have lower positive expectations towards CCS. This translates towards the SDE++ subsidy that is available for CCS, which is affecting the potential continuation of large-scale blue hydrogen projects (most notably h-Vision) due to an unprofitable top, which would be difficult to fund with other types of subsidies.
#2	There is some internal misalignment between actors, since it is not clear who will be responsible for distribution of hydrogen, causing actors to be hesitant to join the niche. This is a consequence of non-clear voicing of expectations and a lack of legislative clarity (from the government), due to which there is no party explicitly responsible for the distribution of hydrogen. This is causing parties to be hesitant to invest in experimentation concerning hydrogen distribution, since the investment could potentially be rendered futile if the government attributes responsibility to another party. Another example of this comes from the Built Environment ESA; since there is no clarity on the path that the government will be taking, even though there are less costly alternatives (that will forego the natural gas grid), like all-electric (with heat pump) and (waste) heat networks, parties are hesitant to invest, since there is a chance that the government will opt for a large scale infrastructural use of hydrogen. The prospect of the Dutch government choosing for hydrogen is making companies hesitant to invest in alternatives, which is stalling the energy transition in the built-environment. To conclude, expectations of the government, even though positive, are not yet clear. This causes companies to be reluctant to enter the niche. The Dutch government is aware of the need for specific policies, but has not yet introduced them due to uncertainty. So, at the moment, the Government contributes to niche upscaling by subsidies and voicing of expectations, although it could increase efforts on both aspects as well as other specific regulations. It is up to the government to voice their expectations clearly and as soon as possible. Even though they have been doing this in favor of hydrogen (especially recently), concrete decisions have to be made soon, which incentivize actors to experiment and move innovations and implementation forward to reach the climate goals (which are perpetually not being met in the Netherlands).

#3	The third barrier stems from the fact that companies often make plans for which no investment decision is made, which is causing external expectations to dwindle. Due to the general positive expectations towards hydrogen in the Netherlands, companies have made plans throughout the ESA, for which either investment decisions take long, projects are perpetually cancelled or never reported about again after public announcements and media attention. Even though there is an immediate good-will towards the companies that make the plans and report about them, due to the accumulation of such events, this seems to have an adverse effect on the (external) expectations of the feasibility of the hydrogen transition. Whether the plans were attempts at greenwashing or genuine, because of this, external actors show a level of skepticism when large-scale projects are announced.
#4	The final barrier comes from the observation that it is usually big companies or independent research institutes that do studies or invest in projects. It is up to smaller companies to also do research and back the expectations (or disprove them), since research by independent parties helps create high quality expectations.

5.3.2 Barriers related to the Network Building

Within the Network Building internal niche process, a number of barriers have been uncovered, which are explained in Table 5.2 and illustrated in Figure 5.2.

Table 5.2: Network Building related barriers

Network Building Barrier	**Description**
#1	Even though most actor groups are included, some network building has been very recent and should have started earlier, which has a lot to do with uncertainty regarding the development and responsibilities. Due to the current lack of a market, the involvement of users in different sectors is especially problematic, and TSOs and DSOs are still not involved enough, which has led to an absence of experimentation of the distribution and service network. Only recently, in the period 2017 – 2019, the important partnership between TenneT and Gasunie was formed. This has to do with the Chicken-egg barrier, in which it is up to key actors to join the network based on positive expectations regarding the niche. These actors should investigate the niche, and based on the future prospect, should invest and have the faith that demand will follow. The expectations and potential of the niche are high enough for parties to be able to afford such a calculated risk. If this does not happen, then all actors will remain unmoved due to waiting on demand (which is waiting on supply) and the transition will not move forward. Finally, Due to a lack of regulatory alignment some actors, mainly from distribution networks have not yet (or only very recently) become involved in the network. This is directly linked to the unclear voicing of expectations (Expectation Barrier #2).
#2	It can be observed that there is some lackluster collaboration between (intra-sector) individual companies (especially in mobility). For example, collaboration between Dutch transport companies, even though learning processes have been shared freely, has in some instances been lackluster from a (financial) collaboration perspective. One of the major barriers is costs, yet companies have not banded together to buy busses or vehicles in bulk in order to decrease costs. Only very recently, this has come on the radar. Thus, network building in an earlier stage could have led to more experimentation earlier; especially if companies would have banded together to buy busses in bulk, since cost is a major factor.

#3	The third barrier is associated with the fact that network building between government and industry should have happened earlier (directly linked to Expectation Barrier #1). From a network building perspective, the transition would have been helped along if the communication between industrial parties, PBL and the government had been better during the preliminary calculations by PBL for the SDE++. These calculations caused backlash from industrial parties, which has had lasting effects on the expectations towards the feasibility of the hydrogen transition (parties have become more skeptical). A positive sign can be found in the aftermath of the backlash, in which the government (mainly minister Wiebes) actively sought communication with prominent industrial parties, after which their expectations shifted and PBL was asked to perform new calculations. After the renewed calculations there are still misalignments in expectations, primarily about the type of CCS that projects like h-Vision will be performing, but also about the fundamental expectations towards CCS. Projects like h-Vision still are not guaranteed with the current version of SDE++ (even though it is not yet final). Thus, earlier and better communication (network building) between the government, PBL and industrial would have foregone the misalignment that happened when the first PBL calculation was published. This would have led to less confusion about the feasibility of the projects. Currently, communication can still be improved, since there still seems to be a misalignment in the fundamental assumptions of the calculations between PBL and industrial parties.
#4	The fourth and final barrier comes from the fact that Network building across sectors should be improved. As explained in Section 5.2.2, there have been some examples of pivotal cross-sector interactions and partnerships, such as 'Tennet with Gasunie', 'AkzoNobel, Pitpoint and Groningen Seaports', and 'Nuon with Tennet'. Furthermore, actors have expressed the necessity of such partnerships, mainly due to the need for increased demand. Nevertheless, much improvement is necessary in this context, particulary between mobility and en- ergy/industry. Most fuel cells have their own production, which is making fuel quite expensive due to the distributed and small-scale production. All stations should take example from Pitpoint in Groningen and form partnerships to provide hydrogen in a more centralized manner. Furthermore, we can also see that AVR, with its new CCS facility (2019) is looking for potential customers for surplus captured carbon. This could be used in the energy sector (particularly in the built environment) for methanization if partnerships are properly formed.

5.3.3 Barriers related to the Learning Processes

Within the Learning Process internal niche process, a number of barriers have been uncovered, which are explained in Table 5.3 and illustrated in Figure 5.2.

Table 5.3: learning Process related barriers

learning Process Barrier	Description
#1	There is still no large-scale experimentation, which is necessary in the near future. The lessons in the private sector were valuable, but still quite limited due to the large scale, which requires substantial funding and time, and thus still a lack of practical experiments with enough scale. Due to the infancy, it is still a matter of time whether business models prove to be practically feasible and lucrative. Since these experiments depend on funding, it is uncertain whether they will be performed. Furthermore, due to the sheer scale of projects, they take time to be completed and should be done on a larger time-scale for results to be validated. Take, for example the Hystock experiment, which is still too small to be physically stored in a salt cavern. A larger scale (20 MW) follow-up is necessary to physically test storage and validate a potential business case. Also, in the North-Sea developments, actors have expressed the need for larger scale experimentation (potentially in the form of an energy island), which has yet to be done. Thus, a lot of these learning processes are quite recent and still need to be proven in practice (also to gain more first-order learning). Due to the scale of this transition, first-order learning has been limited and learning processes have only recently resulted into practical actions (HyStock) and solutions. Additionally, there have been and are still some issues holding back optimal learning, which need to be addressed soon.
#2	There is a need for further experimentation, which could for example, give clarity to the Dutch government with regards to the optimal SDE++ funding. With current technological progress there is a dominant design already. This dominant design is being tested for first-order learning in order to make efficiency gains and gain learning processes on other performance criteria, such as the optimal running time (6000 as opposed to 8000 hours). This debate can also give clarity to the Dutch government with regards to the optimal SDE++ funding.
#3	Learning processes are in a very early stage and simply need to continue. Dutch industrial actors have learnt that in order to have a successful transition, technical improvements have to be made, especially to lower the production costs. Learning has therefore often been performed especially with this goal in mind. With regard to blue hydrogen, several actors have experimented with different production types in combination with different CCS types. These learning experiences, are still in a very early stage, which do not conclusively show improvements, in terms of efficiency and cost. In the TNO study (2017) it became clear that it would quickly lead to a CO_2 reduction, even before the feasibility study was completed in 2019, they had already clearly announced this in 2018. The stakeholders were also very certain about technical aspects.
#4	The fourth barrier is closely related to Expectations Barrier #1, since misalignment in expectations has limited some projects' ability (most notably h-vision) to successfully experiment and test hypotheses from the feasibility studies in a timely manner. When it comes to practical experiments, the debate regarding subsidies for CCS projects from SDE++ has limited some projects' ability (most notably h-vision) to successfully experiment and test hypotheses from the feasibility studies in a timely manner. This is worrisome, due to the perceived function of blue hydrogen as a transition step towards green hydrogen. Research institutes (CE Delft), multiple private parties (through independent research) and validation interviews have expressed the same expectation; namely that the Netherlands should start immediately with implementing blue hydrogen in order to make the needed efficiency gains, create market and gain technical as well as social learning processes. This expectation extends to the fact the green hydrogen will undergo inevitable cost reduction through technological improvement until around 2030, meaning that until then, the necessary learning processes should be undergone through large-scale blue hydrogen implementation. If this parties wait too long with this, it could possibly be detrimental to the hydrogen transition in the Netherlands.

#5	The SNM analysis has uncovered that there is a need for more institutional support for experimentation. actors, validated by interviewees, stress the need for better institutional support, particularly on clearly assigning responsibility to which parties will be responsible for distribution (private or DSO/TSO or something else), in addition to tax and subsidy arrangements (since currently hydrogen blending is not seen as renewable in the current system, which is hindering companies from getting involved) for suppliers. In this context, a TNO study concluded that many more parties would invest if there was clarity about, which is validated through interviews. This is making parties hesitant to get involved, especially in distribution, which has an impact on learning (no experimentation leads to decreased learning). As a consequence, another critical aspect appears to be the difficulty to act upon the theoretical lessons learnt about the need for an enhanced distribution network.
#6	There is a lack of buyer-supplier interactions, due to which knowledge is lacking on how the consumers perceive the technology, the extent to which it fulfills their needs and the impact it has. Because of the lack of buyer–supplier interactions, due to a market that still needs to grow, knowledge is lacking on how the consumers perceive the technology, the extent to which it fulfills their needs and the impact it has. There is also a need for more intra-sector connectivity, which is also partly due to the sheer infancy of the niche. Households are practically not in the picture for hydrogen on a large scale any time soon and hydrogen cars are still lacking (+/- 200 cars) and only 5 refueling stations.
#7	Throughout the ESA it has become clear that time between learning processes and governmental decisions can tend to take long, which causes the transition to be slower than it could be. A couple of practical examples can be found throughout the ESA. (1) Firstly, when it comes to hydrogen mixing in the natural gas grid, experiments as early as that in Ameland (2008 - 2012) have concluded that the transition would be helped if mixing in the natural gas grid would be increased, with preliminary results showed this to be (technically) possible. From then onward, there have been multiple experiments that have come to similar conclusions. Furthermore, countries that are performing better than the Netherlands with regards to hydrogen implementation (including Germany) have higher allowed percentages. The studies have not been conclusive, stating that more research is necessary, yet the government has not yet dedicated research towards this. (2) Secondly, from the mobility sector's ESA, it has become apparent that the introduction of (European) standard can be highly effective from both a technical and a financial perspective (European grants could be obtained in 2018 as a result of the standard in 2017). Nevertheless, because of waiting for such standards to be researched by the EU, there is quite some lag, causing Dutch experimentation to stall. The Netherlands has expressed to want to wait for a European mixing standard, which is taking quite some time. (3) The same counts for policy reform, which is deemed necessary by industrial parties, when it comes to viewing hydrogen as a sustainable fuel (which would incentivize them to use it over biogas).
#8	Finally, a lot of projects in all sectors are currently held back or investment decisions take long, which leads to a lack of practical experience and necessary learning processes. This barrier is directlty linked to Expectations Barrier #3

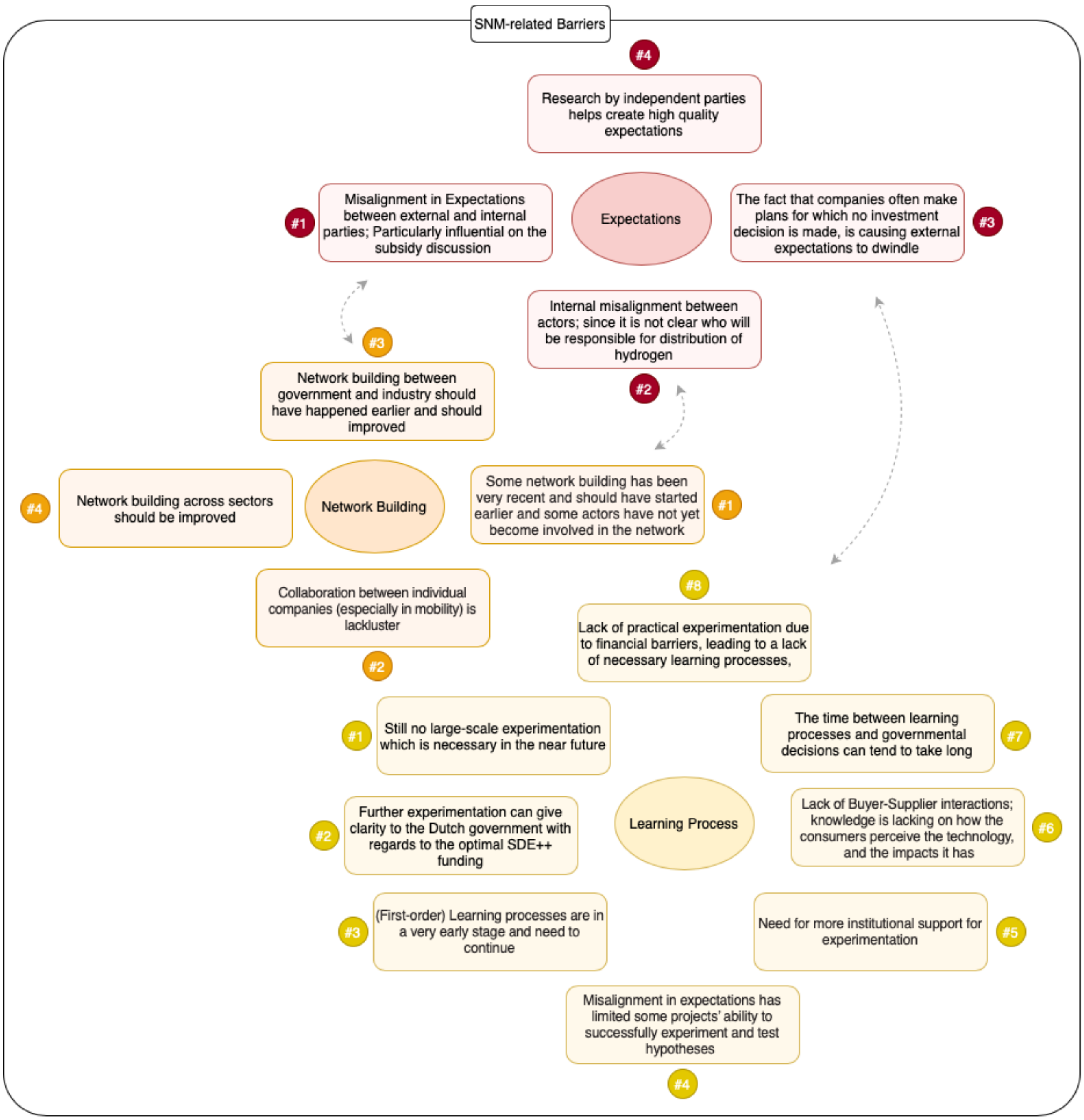

Figure 5.2: Barriers towards hydrogen upscaling uncovered from the Strategic Niche Management analysis

Chapter 6

Discussion

6.1 Scientific Novelty

6.1.1 Novel combination of theoretical and methodological approaches

This study is the first to apply the ESA methodological approach to transitions research (specifically to SNM and MLP), in the way that it has been presented in the thesis. This application was necessary due to the shortcomings of the usual methodological approach (stemming from the multivariate perspective) that is associated with transitions research, which focuses on global (historical) snapshot within singular domains, with interviews as primary data. Such an approach was deemed unsuitable for the comprehensive analysis of the hydrogen transition, which is particularly complex due to its (synergistic) dependence on multiple niches that are implemented in different sectors. The application of the combined framework (SNM and MLP) and methodology (ESA) proved very suitable for the analysis of such a large transition over a large period.

Furthermore, these approaches complement each other in multiple ways. Firstly, while transitions theory posits the necessity of viewing a transition as a stream of events, where it matters when a specific event takes place. This is the basis of the process perspective, from which the ESA framework is derived, which views reality as a 'stream of events.' Secondly, through the addition of this research, a transition pathway can not only be mapped and analyzed, but it adds quantitative rigor due to the replicability and quantifiability, to the otherwise qualitative study. By visualizing and describing the event results and the conclusions that are derived, the research becomes much more tangible.

The ESA methodology provided significant added benefit for the SNM application, due the way in which data can be collected and visualized. The importance of timing of certain 'Events' (experiments, voicing of expectations, formulation of visions, etc.) in ESA has great alignment with SNM theory with regards to the analysis of the internal Niche processes. The process perspective indicates: "Extremely minor events can have a large consequence because of their location in a sequence" (Spekkink, 2014). This is in line with what is stated in by Turnheima and Geels (2019) with regards to SNM: "the early formulation of highly specific visions can effectively guide search paths" and "particularly influential projects (which we call 'landmark projects') can be decisively accelerate innovation developments." This made it valuable to visualize events with ESA to chart how effective the visions of the clusters or regions have been, by looking at what events have resulted from that. In addition, there are more advantages of ESA methodology for SNM, such as taking into account 'unplanned events' instead of just 'planned, well-ordered and consensual management processes', with which SNM is often criticized (Farla et al., 2012). This methodology has also been useful to look at the outside influences (Boons, et al., 2014), which in turn fit well with the MLP.

6.1.2 Theoretical delineation of hydrogen clusters

Throughout the literature (Hermans, 2018), it became clear that the hydrogen transition is complex and differs from what is usually covered in transitions' theory (technologies like Solar PV and Wind Energy). Due to the sheer scale of hydrogen and its different applications in various sectors. Furthermore, the transition focuses on cluster formation while transitioning, all whilst the companies are usually also embedded within the regime. Through the adaption of Markard and Truffer's (2008) proposed TIS (combining IS with MLP) framework, this thesis applies a visualization and delineation of hydrogen clusters, which can be used for future studies. Perhaps the TIS framework's analytical strength can also be used in future studies. This delineation has proved all-encompassing and very instrumental in the approach on how to analyze the hydrogen transition.

Because of the ESA approach it was important to define a 'central subject': "To define something as a process is to define a central subject as well as the different types of events that the central subject endures or makes happen. The central subject can be any entity, such as an individual actor, a group of actors, a lineage, a social movement, a machine, or a RIS" (Spekkink, 2014). This fit well with the merged FIS and MLP framework proposed by Markard and Truffer (2008), which has been adapted and used to guide the otherwise complex research delineation. Concluding, ESA has proved to be a good addition to SNM and a promising alternative to interviews as primary data, which can be very data intensive (Boons, et al., 2014; Spekkink 2013).

6.1.3 Contributing to the body of literature for SNM and MLP (and ESA)

Concerning the theory on transitions, this thesis contributes to the understanding that a combination of Strategic Niche Management (SNM) and the Multi-Level Perspective (MLP) can effectively contribute to the analysis of the implementation of Niche technologies to analyse how the transition has been handled and how it can be facilitated in the future (with the goal of gaining market share within the regime or eventually take-over the regime). By visualizing with the ESA, it became clear how the higher levels of aggregation influence the transition pathway. Especially the Landscape influences have mutual influence on all levels of society and especially on all relevant sectors (simultaneously). Furthermore, this thesis clearly shows the importance of these higher levels of aggregation; successful innovations do not arise in a vacuum, but they are influenced by current regimes and the social context. A well-designed experiment should exploit (temporary) instabilities in the dominant regime or landscape (MLP) by looking at 'destabilizing shifts' and taking advantage of those. As can be seen by the analysis of the implementation of hydrogen in the Netherlands, it is important to create protected spaces (due to financial barriers). Yet, even though protection by financing can contribute to a technology's adoption, this thesis also shows that it is equally as important to communicate expectations well - so that adopters' expectations can be aligned - before such funding is provided.

6.1.4 Contributing to the body of hydrogen literature

As discussed in Chapter 1, the body of knowledge on the hydrogen transition is very small. Furthermore, the bulk of the research has been on the technical and financial feasibility of hydrogen (especially in the Netherlands). Through these studies, the technical feasibility has been proven (to a certain extent) and it has become clear that there are financial barriers. Nevertheless, there have been no studies on the effectiveness of the implementation in the Netherlands. This thesis adds to the body of hydrogen knowledge by evaluating the implementation and giving recommendations on how this can be done better.

Furthermore, the thesis adds to the literature by providing a unique in-depth insight into the historical implementation in a European country (the Netherlands) by analyzing expectations, learning processes and network building (SNM) surrounding this implementation to analyze how it was handled and how the relevant stakeholders reacted to this, within the bounds of the Socio-technical Regime and with the influences of the Landscape (MLP). Furthermore, due to the broadness of the MLP analysis, the specificity of the claims made by the research on key Landscape (and Regime) events, the qualitative data gathered for this thesis can be used by other researchers covering hydrogen (transitions) research globally (especially for other Western European Countries).

Due to the Breadth of data gathered, this thesis adds to the inventory of all relevant experiments and events in the Netherlands, what the results were and how they affected the transition. This can be used as a reference or database for relevant actors to see what events have been done from 2000 to 2020. This has several practical implications, e.g., they could use results of previous experimentation as inspiration or input for new projects.

6.2 Limitations

6.2.1 Time Constraints

The Event Sequence Analysis (ESA) approach is very data-intensive, as it requires the collection, processing and analyzing of longitudinal data that spanned over a long period of time (Spekkink, 2013). Furthermore, Boons, et al., (2014, p. 347) indicate a similar opinion: "data must cover a substantial time period, and data sources may not be available for all theoretically relevant events." This had the implication that, due to the relatively limited time, the researcher had to make choices and focus on the major and most relevant events. Thus, even though the event map in Figure 4.8 in Chapter 4 is as comprehensive as it could be within the time limitation, some (potentially pivotal) smaller events might be missing. Furthermore, due to the time limitation, the events that were mapped could not all be studied in-depth, and a more global view was taken. Time constraints have also inhibited the amount of validation interviews could be performed, which had the simultaneous function of gathering additional data on internal Niche processes. This limitation also affects the recommendations that can be given, since the sector-specific and internal niche barriers that have been uncovered in Chapter 4 and Chapter 5 are quite complex. Therefore, they should be subject to further research in order to be better understood. By backing them with research, they have more of a chance to be overcome. Finally, due to the time constraint, even though an explicit focus was on international events, there was less of a focus on examples from other, more accomplished companies. Nevertheless, this was also a consequence of the infancy of the transition leading to a lack of research reports.

6.2.2 Infancy of the Hydrogen transition

Due to the infancy of the transition, a choice was made to focus on the transition pathway for the whole of the Netherlands (in all sectors), as opposed to zooming in to do an in-depth analysis of the dynamics within key events. Even though these were taken into account, they were done from a broader perspective. A choice could have been made to focus on a select group of events, perhaps with a focus on events that originate within (industrial) clusters. However, due to the lack of practical applications in the Netherlands, at this stage of the hydrogen transition, a broader view – as taken in this thesis – yielded more concrete results. If the barriers uncovered in Chapter 4 and Chapter 5 are addressed in a timely manner, the research should be revisited with a more in-depth view on e.g., Niches that form within the major clusters. Due to the infancy of the transition, along with the large-scale nature of hydrogen niches (particularly in the Industry and Energy sectors), experimentation has lagged. This limitation has therefore directly affected the SNM research due to its dependence on practical experimentation. As a result, this has implications for the concrete recommendations that can be given, since this is partly contingent on results from experiments.

6.2.3 Novelty of the methodological approach

Due to the novelty of the approach (ESA with SNM and MLP), there was a lack of previous studies or example researches to utilize, hence the research process and set-up was not optimized. This brought a multitude of challenges with it, most notably:

- The coding software is novel and had to be learned, after which a coding scheme had to be made, based on the theoretical framework and ESA concepts, which had to be done from scratch without similar examples;
- The visualization tool that came along with the coding software also had to be investigated. Once familiarized, and validated event maps were created through different iterative rounds, the way that the maps were visualized, based on SNM and MLP had to be figured out without examples. This made it a lengthy and iterative process until the Event Map in Figure 4.8 was created.
- The novelty of combining ESA (which is data-intensive) with a large-scale transition like the hydrogen transition made it challenging to make a concrete planning, which made an iterative process pivotal.
- A final challenge, which came after the long data-collection process, was the way in which the data should be described. This was mainly due to the fact that there were no similar papers to take as inspiration, heightened by the fact that the data-collection had provided a wealth of in-depth information which was necessary and important for the research and its conclusions, but which had to be summarized in a clear manner.

6.3 Implications

6.3.1 Implications for Researchers

For researchers, this thesis has several major implications. Firstly, this thesis proves the applicability and utility of conducting an SNM study from a process perspective (with ESA). Therefore, from a theoretical and methodological perspective, researchers could utilize this research as a basis for future transitions' studies. Secondly, the breadth of accumulated data through this research can be used as a springboard for further hydrogen-specific transitions research. Finally, it can be used as an example of how to approach projects in the future, and which experimentation is worthwhile.

Since hydrogen is at a very early stage, it is an ideal test-case for the following (far-fetched) suggestion: theoretically, this ESA can be used as the basis for a database - since all relevant events have been mapped from 2000 – 2020 -, in which all 'relevant' future projects are logged (potentially by the initiators themselves), for which the results can also be added later on. By filling this in, a national log can be made with results of experimentation and e.g., changes in underlying assumptions due to this. This could be used for follow-up evaluations by internal or external actors or as governmental legislative considerations; it can serve as a database for actors who want to do further or new experimentation in a way that information is shared freely in the benefit of everyone. This could ultimately be used for future research to evaluate the transition's performance and steer it in the right direction ones more.

6.3.2 Implications on Sectoral Policy

As uncovered by the ESA (Chapter 4) and SNM (Chapter 5) analyses, one of the most critical factors for the development and upscaling of hydrogen is stimulating and facilitating policy. The demand for financing is currently larger than the supply; in light of the large-scale nature of the transition towards hydrogen, on the short- and long-term, the current (financial) resources are simply insufficient. This does not necessarily mean that the implementation has been lackluster up to this point, there are simply some barriers to overcome in order to reach full reach upscaling and full maturity of the niche. As seen in Chapter 5, the implementation of demonstration projects has performed quite well from an internal niche process perspective. It is pivotal that the niche implementation phase continues to improve the niche processes and continues innovating. For these niche implementations to continue, there is a need for (significant) innovation subsides for new designs, as well as a need for continued support during the operational phase.

It is in these initial and operational stages that the costs are unproportionally high (especially for an expensive niche such as hydrogen), compared to fossil fuels. Therefore, a large amount of niche protection is needed to incentivize actors to innovate. This is also at the core of the SDE++ discussions, where subsidizing the price for acquisition is not adequate according to the stakeholders. Such financial support in the form of an operating subsidy - e.g., a subsidy per produced kg or per averted CO_2 emissions - seems to be pivotal due to the high costs, which should in principle be justified due to the public interest in achieving the climate targets. Due to the long-term and large-scale transition that would be necessary for hydrogen, it is also pivotal to have long term financing structure. For this it can be seen throughout the ESA that involvement of financial institutes in projects or active voicing of positive expectations towards these institutes (e.g. banks, pension funds and venture capital providers), in order for them to develop the needed knowledge or incentive to provide financial support towards the hydrogen transition.

This section presents the implication that this thesis has on sectoral policy; how the theme of hydrogen can be developed in the coming years and which priorities can be identified for this. This proposal is based on the barriers and windows of opportunity uncovered in Chapter 4 and 5. The following implications arise, which consists of 5 practical implications along with the structure in which it should be embedded in order for upscaling to optimally happen (visualized in Figure 6.1). First the practical implications are discussed, after which the system in which it should be embedded is laid forth.

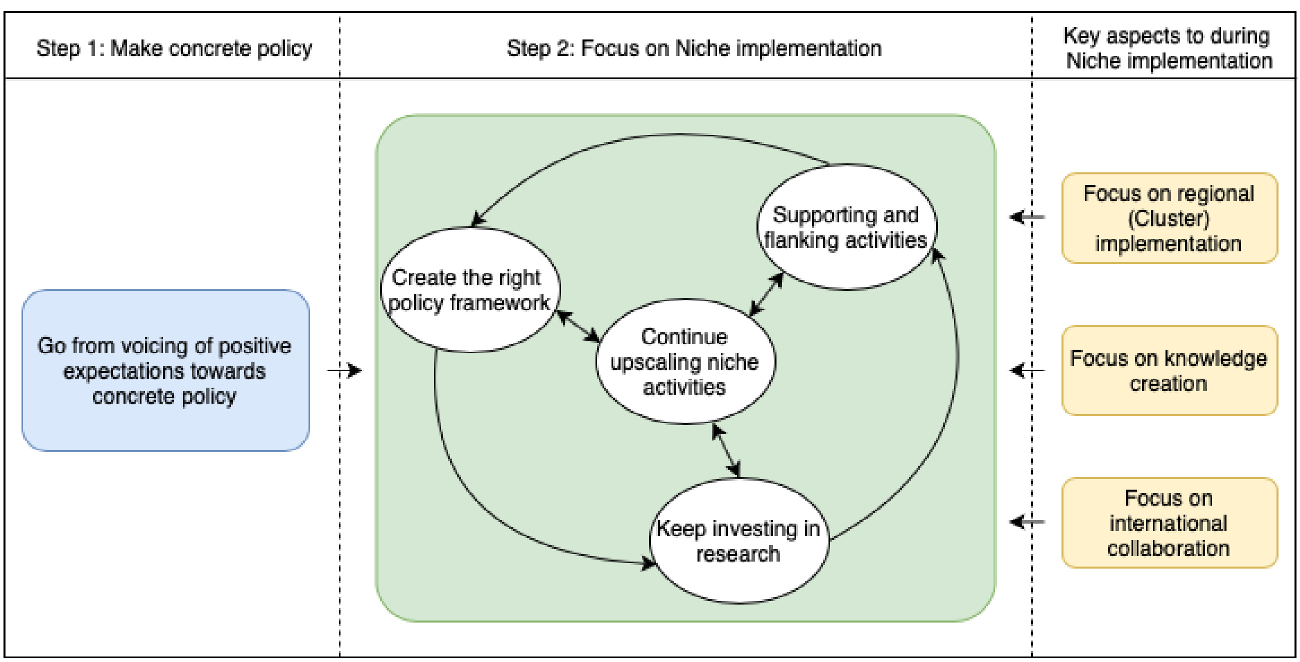

Figure 6.1: Sectoral implications and considerations that are uncovered through this thesis

6.3.2.1 Go from voicing of positive expectations towards concrete policy

As seen from the conclusions from Chapter 5, there is a need for clear vision about the role that is attributed towards hydrogen in the future Dutch energy (and raw material) system and how this will be achieved with practical steps. For this vision, the initial and largest role is attributed towards the government, since actors need to have clarity about which future developments to invest in and how this will be incentivized and supported by policies and regulations. To stimulate governmental decisions, it is pivotal that sectoral actors, citizens (users) and other (involved) stakeholders will have to voice expectations and make their commitment and ambitions known.

Table 6.1: Necessary actions to move towards concrete policy

Need for a concrete vision for hydrogen (from government)	**Involved Parties**
There seems to be a necessity for a long-term policy stipulation, both through the acceptation of the energy carrier as a green energy carrier (for benefits like excise duty exemption) and financial support of the operating costs through an SDE++-like structure in order for the unprofitable top of business cases for project to be covered. Furthermore, from a strategic point of view it is important to gain insight into the specific role that can be attributed to hydrogen in the future (in which the ambitious climate goals are met) and which market the and applications the energy carrier can best serve.	Mainly Government (EZK), but all stakeholders should be involved.
Need for studies and analyses for program development	**Involved Parties**
Through the continuation of studies (by independent parties) it can be uncovered which hydrogen developments are most desirable and how hydrogen relates to alternative options from a Dutch, as well as a European perspective, in order to clarify the most beneficial production methods and applications. Furthermore, due to the financial barrier, there is a need to uncover how hydrogen implementation should be handled from a fiscal perspective (excise and energy tax, next to operational support) through a stable long-term policy that incentivizes investment in order for the business case to be stably determined. Finally, similar to the highly influential CE Delft (2018 study), future studies should contribute to the upscaling process necessary to reduce investment costs for hydrogen technology.	all stakeholders, collaboration with planning bureaus (PBL, CBS), CE Delft and TNO System Studies, consultancy firms (Accenture, Royal Haskoning DHV, Arcadis).

6.3.2.2 Create the right (policy) framework

As described in Chapter 4, there is a plethora of topics associated with the hydrogen chain that is essential for the upscaling of hydrogen implementation (to take over the niche), like modification of hydrogen infrastructure, standardization, gas quality (including blending hydrogen in natural gas), large-scale storage of hydrogen, tank infrastructure for mobility and transport, import of hydrogen and the position of ports, and system integration of (offshore) electricity production. Most of these topics have been discovered and discussed during practical experimentation, nevertheless, there are some topics that need to be actively sought out in order to make them subject to study to consider and weigh out the pros and cons to come to the most optimal design. Further study would then be necessary to uncover what the costs are and how it should be implemented. Studying such topics (that do not necessarily come from practical experimentation) is pivotal since with hydrogen it usually concerns large-scale, costly choices that need to be integrally weighed (from a national and international perspective).

The most notable topic is that of hydrogen system function, since it is still quite theoretical and not much is known about the practicality of hydrogen's potential to offer flexibility for the energy system through storage (gas-to-power), what the (best) infrastructural options are (e.g., landing of offshore electricity via hydrogen created on the North-Sea) and what the most optimal configuration would be for such a large-scale system. Even though the first pilots are in preparation in this area (for example electrolysis on a production platform in the North Sea), there is necessity for more studies and experimentation, e.g. in the form of a "test energy island" with the complete system for wind hydrogen at sea on a small scale and under realistic conditions.

6.3.2.3 Supporting and flanking activities

Next to the creation of the right policy framework, there should be a simultaneous focus on developing the right auxiliary condition under which hydrogen implementation can flourish, like hydrogen certification - uniform European system for Guarantees of Origin for (green) hydrogen, certificates for green hydrogen and hydrogen with a low fossil carbon impact -, social embedding, the role of clusters (or other important regions). A role is designated for the government to do this, but it is important to actively involve such themes within practical projects as well. Some topics might not be held back by financial barriers, but, for example, due to the indecisiveness or the lack of positive expectations from the most relevant and influential actors or a lack of collaborative effort. Finally, a concerted effort should be made towards International coordination and cooperation, due to the immense influence of international parallel niches uncovered in Chapter 4.

> The most relevant actors that should be involved with supporting and flanking activities include: *ministries, industry, local / regional authorities, advisers, knowledge institutions*.

6.3.2.4 Continue upscaling niche experiments

Next to gaining experience, large-scale practical experimentation can reveal the necessary research and development, which bottlenecks (such as legislation and regulations, permits, safety, availability of subsidies) must be tackled for increased upscaling and what the financing plan should look like. Furthermore, from a network building perspective, it becomes necessary to gain insight into which composition of actors (consortia of concrete parties) can be formed to implement the development plans most optimally. These plans could be elaborated by program teams, for example in the clusters, in which the relevant stakeholders are represented. Such teams are (partly) already available, such as Hydrogreenn Hoogeveen, H-vision Deltalinqs and WaterstofNet. Furthermore, the H2Platform plays an important role with regard to demand aggregation. Finally, for a majority of the niche implementations combinations and links between sectors are possible, useful and necessary due to multiple reasons: cooperation, coordination and clustering (both local and regional as well as national and international) accelerates knowledge development and increases support, leads to shared infrastructure and economies of scale, and increases the chances of effective policy and sufficient financing options.

Mobility Sector

Table 6.2: Necessary Mobility sector action

Roll-out of mobility on hydrogen, including the necessary filling points	**Involved Parties**
Hydrogen in the mobility sector is most advanced compared to the other sector, where much of the necessary technology (cars, buses and filling stations) is already available. Nevertheless, the technologies are still not mature and need improvements and optimization (mainly to reduce costs). On the other hand, for the heavy transport development is still much needed. The most important preconditions are favorable running costs of vehicles (TCO = Total Cost of Ownership). The improvements should focus in particular on the following, with simultaneous developments in supply and demand. Firstly, in order to be able to develop hydrogen mobility and transport in various sectors, a nationwide infrastructure is necessary. That is why the current 4-5 filling stations need to be scaled up. In addition, improvement of the filling points is necessary in view of the investment costs, efficiency and maintenance. For promotion of the adoption of hydrogen vehicles (cars and buses), a nationwide coverage of hydrogen filling station is pivotal. Next to this, for cars specifically, there is a simultaneous need for the continuation of market activation and introduction (low addition, exemption from BPM, MRB and excise duty on hydrogen, residual value guarantee fund, etc.). For fuel cell electric buses support is needed for further expansion of use in concessions where battery electric buses are not sufficient. Stimulation can be done through regular channels (concession).	freight carriers, public transport companies, municipalities and provinces, diverse range of vehicle manufacturers, service station operators, filling point manufacturers, hydrogen producers/suppliers.

Energy Sector: Power-to-Gas as system function (Electricity)

Table 6.3: Necessary Energy Sector: Power-to-Gas as system function (Electricity) actions

More Demonstration and pilot projects	**Involved Parties**
In this sector, demonstration projects are also pivotal due to the relative infancy of implementation, especially towards the possibility of green hydrogen in relation to the integration of decentralized sustainable electricity generation and the relief of bottlenecks in the electricity grid. At different nodes there are network capacity limitation, which is limiting the inflow of decentral renewable energy (from solar and wind) into the grid, which is a major barrier for renewable energy projects. In such situations, the interconnectivity between sectors can prove pivotal, where a local connection can be made with a hydrogen filling station or with built-environment applications, by e.g., mixing hydrogen in the regional natural gas grid.	electricity producers (large and small-scale), network operators, local/provincial authorities, Dutch manufacturing industry.
Realisation of a Test Energy-Island (North-Sea)	**Involved Parties**
Due to the Netherlands' commitment to increasing off-shore wind energy to reach the climate goals, and the expected challenges and bottlenecks with regard to transport and landing of this electricity, there needs to be a realistic test-bed for testing the testing a complete system for "wind hydrogen" at sea, including the necessary infrastructure such as offshore hydrogen pipelines. This will allow experience to be gained on how this option can be used efficiently and reliably in the future and can bring together the right consortia of actors. Plans are being developed for several large "energy islands" in the North Sea where hydrogen could be produced with electricity from wind.	wind energy producers, grid operators, local/provincial governments, Dutch manufacturing industry.

Energy Sector: Power-to-Gas for the Built Environment

Table 6.4: Necessary Energy Sector: Power to Gas for the Built Environment action

More Demonstration projects	**Involved Parties**
Due to the relative infancy of experimentation in the built environment, as compared with the other sectors and the diverse options for making the sector more sustainable, there is a need for more demonstration projects with hydrogen to gain experience and optimize the process. The application of green hydrogen seems to be most attractive for the heating of buildings where the other options are infeasible (e.g., old buildings in city centers with bad isolation). In order to reach the climate goals in the built environment it is essential to research and test how hydrogen can best be implemented in such buildings or areas that have a lack of other options, as well as the continuation of demonstration projects in normal residential districts (like Hoogenveen and Stad aan 't Haringvliet) to gain experience and to be able to determine conditions under which conversion, application and any further roll-out can take place effectively, efficiently and safely. Research questions most critical in this sector are (1) mixing of hydrogen and natural gas in an existing situation, (2) pure hydrogen in an existing neighborhood, (3) Application for individual residential homes and (4) Application in collective heat systems.	construction sector, project developers, housing cooperatives, municipalities, network operators, installation sector, residents.

Industry Sector

Table 6.5: Necessary Industry Sector actions

Production (Scale-up necessary)	**Involved Parties**
In order to serve the future demand for hydrogen sustainably, large-scale production of green hydrogen – through electrolysis – is essential. Scaling up through larger amounts of electrolysis factories and larger capacities of such systems will lead to cost reductions. As seen in Chapter 4, several plans for a growth trajectory to 3-4 GW by 2030 have been launched, through an upscaling route from the first 20 MW installations now under preparation through 50, 100 and 250 MW projects to GW scale, but investment decisions need to be made. taken, for which sufficient funding must be released. Major challenges are also the future availability of renewable electricity, the availability of electrolysers on a larger scale, the development of the demand for hydrogen and the financing and exploitation of these projects. It makes sense to achieve upscaling in industry (including refineries) because of the potentially high hydrogen demand. Next to green hydrogen, blue hydrogen needs to be simultaneously promoted, which is a more short-term option to supply a large amount of climate neutral hydrogen for, e.g., the industry and energy sectors for flexible electricity generation. It is pivotal for green hydrogen to scale-up while blue hydrogen is also being implemented. As described in Chapter 4 the first initiatives in this area is the H2Magnum project of Vattenfall, Gasunie and Equinor in Eemshaven and the h-Vision project in Rotterdam. Financing and exploitation are also important challenges here.	chemical industry, large companies, Dutch manufacturing industry, electricity sector, ports;
Infrastructure (need for a “Backbone” that connects clusters)	**Involved Parties**
If hydrogen will be produced on a large scale, a hydrogen infrastructure is pivotal to supply the different of production and usage-cluster with green and blue hydrogen. For this, the creation of a hydrogen “backbone” on both a national level – with which the storage of hydrogen is directly connection – as well as hydrogen in distribution networks for the built environment. It is likely that conversion of (part of) the natural gas infrastructure will suffice, possibly supplemented with new infrastructure where the existing infrastructure is not available or suitable.	Gasunie GTS, regional network operators, Dutch manufacturing industry.

6.3.2.5 Keep investing in Research

For hydrogen, since it is such a novel niche with many open research questions and a necessity for optimization, there is a need for short- and long-term investment in research to be able to develop hydrogen across the board and for the full range of applications. Furthermore, some results are needed earlier, but require more fundamental solutions that require more time. A differentiation can be made between:

1. **Production**, where the most posing research question pertains to green hydrogen and which variant of electrolysis is best suited for upscaling (leading to lower costs and higher efficiency),

2. **Infrastructure and storage**, where short-term decisions need to be made, since they are important for upscaling and for linking the production and use of hydrogen, and

3. **Applications**, which is challenging due to the immense diversity, but across the board, important themes concern the development and optimization of fuel cell systems for various applications and adaptation of equipment, such as burners and engines, for hydrogen.

Due to the urgency of the hydrogen transition, it is pivotal that short (er) term R&D questions be tackled quickly to achieve necessary upscaling. These short-term R&D questions will most likely be supplemented through practical experimentation, therefore it is essential that actors show enough flexibility to intercept and take on the challenge of answering those questions in an interactive and effective manner. Due to the infancy of the hydrogen transition, the expectation is that on a long-term, there are many fundamental improvements attainable concerning production and application. Importantly, it seems that hydrogen can provide a solution to societal segments that are difficult to make more sustainable. In order to do so, however, long-term investments in R&D continue to be pivotal.

> The most relevant actors that should be involved with investing in research are diverse, but mainly include, *governments, research and knowledge institutions*

6.3.2.6 Embedded system towards optimal hydrogen niche implementation

Focus on cluster formation and regional embedding
As can be seen from the theoretical discussion in Chapter 2 and from practical experimentation in Chapter 4 (especially in the Industry sector), collaboration to work towards the energy transition should eminently focus around the 'landing places'; this is almost always the physical locations around the (industrial) harbors or logistics centers, most notably the Northern-Netherlands and South-Holland clusters. These clusters provide excellent conditions to expose a large plethora of societal actors (provider, operator, user and the broader environment) with the niche in order to gain learning processes, through which expectations can increase and ultimately attract all relevant stakeholders to niche experimentation. This ultimately leads to improvement of the niche implementation and causes a feedback loop which re-enforces and optimizes new niche implementation. From an SNM perspective such regional embedding is critical due to the necessity of practical experimentation for upscaling. Furthermore, as uncovered in Chapter 4, the associated technologies in most cases is developed enough to be practically implemented as a technological niche or even market niche. From an SNM perspective it is pivotal to do so, especially in mobility and the built-environment, the technologies are novel and come in contact with the societal layer, for which it is important to undergo learning processes in practice. Without this feedback loop, the societal layer can feel neglected and estranged from the technology, which will cause significant barriers acceptance and future implementation.

The goal with practical experimentation should be to emphasize societal (socio-technical) aspects of implementation in order to optimally learn and create so-called feedback loops to learn and optimize future implementation, while attracting more actors to the niche and increase the overall expectations of its success; pivotal here is the involvement of the societal layer to increase acceptance. If the regional embedding uncovers the potential for practical experimentation and express positive expectations, the necessary (regional) actors can be attracted and become involved for the execution. In this way synergy effects can come into play through clustering of activities within specific regions to reduce costs. Not just for the execution of projects alone, but also for local authorities to gain experience with policy frameworks that apply to hydrogen projects with the aim of optimally developing these projects. Finally, it is also pivotal for intra-region collaboration and lateral sharing of knowledge and experience. As can be seen from the ESA, Northern-Netherlands received the most substantial European Subsidy with a sub-goal of creating a Hydrogen valley which would serve as an example for other European states; this further emphasizes the need for regional (or cluster) approach towards hydrogen implementation.

International Coordination
As one of the main barriers uncovered in Chapter 4, the hydrogen transition is very large-scale and projects are relatively expensive due to the novelty of technology that still needs to be further developed, that has not yet undergone mass-production efficiencies, with suboptimal institutional frameworks. Furthermore, the lack of infrastructure also still needs to be adapted before use, which is re-enforced due to the lack of sufficient scale. One way to circumvent this issue is through increased international collaboration, especially through research, demonstrations and implementations of hydrogen technology; because of the large investments and the necessary resources, knowledge and expertise necessary, the Netherlands cannot overcome the challenge with an isolated view.

As can be seen from the ESA in Chapter 4, Global and European hydrogen developments and funding were pivotal for stimulating or influencing the Dutch hydrogen pathway. Throughout the development, many international instances were established to promote collaboration (most notably FCH JU) and there was a wide range of international projects from which Dutch organizations received funding or within which they collaborated. It is pivotal to continue these collaborations in the future; this can be through bilateral collaboration with other countries (with the UK (Leeds) for the Built Environment or with Germany (Audi) in mobility and industry)) or in large European projects.

On the other hand, the Netherlands can also serve as an example country due to its relatively prominent position when it comes to hydrogen transition. It can also serve as a testing ground for new developments due to its the strong suits when it comes to the energy carrier, such as the presence of an extensive gas infrastructure, a strong chemical sector, a large transport sector for road and water transport, and activities in the North Sea (blue hydrogen, the combination of offshore wind farms and green hydrogen production). The presence of a high-quality (gas) knowledge infrastructure also contributes to this.

Focus on knowledge creation
Hydrogen as an all-encompassing energy carrier is a relatively new field of study and implementation (starting around 2000); even though it has been used in industry for decades, the implementations in mobility, the built environment and as for its system function in electricity are new. Because of this, there is a need to facilitate activities aimed at developing the specific knowledge and expertise that the energy transition requires in the field of hydrogen in the coming years. This expertise lies in a wide range of areas, such as working with gases, under high pressure, in extreme cold, in stationary and mobile applications and in various environments (industry, built environment, mobility and transport, on- and offshore). many areas (infrastructure, storage, applications) and requires (the combination of) different disciplines, such as technology, economics, institutional affairs and social aspects.

6.4 Societal Relevance

From an academic point of view, it was interesting to analyze if the current plans regarding hydrogen in the Netherlands have set the right precedence for large scale implementation. This is specifically useful to the government and the society of the Netherlands. The European country will be able to take aspects sketched in Table 6.6.

Table 6.6: Societal relevance

Societal Relevance	
1	The role that the government of the Netherlands can play to improve their energy situation
2	What the main obstacles are to consider when designing a hydrogen economy
3	Who the relevant actors are that participate in the hydrogen niche (with respect to expectations alignment and network building) (see Table B.3).
4	Other stakeholders can now realize the potential and how to mobilize for deployment of hydrogen studies and experimentation

Chapter 7

Conclusion

This thesis started with the Research Question (RQ):

Table 7.1: Research Question

RQ	"How has the hydrogen niche been developing in the Netherlands, and how can this be facilitated?"

This was subsequently subdivided in 5 Sub-questions (SQ):

Table 7.2: Sub-Questions

Sub-Questions	
SQ1	"What are criteria for good hydrogen niche development over time?"
SQ2	"How can the progress of the hydrogen niches and the emerging transition be studied over time?"
SQ3	"How did the hydrogen niches and the emerging transition evolve over time?"
SQ4	"What patterns can be identified in the hydrogen niches?"
SQ5	"How can the emerging hydrogen transition be stimulated?"

All of these questions were individually answered throughout this thesis by using two intertwined frameworks: Strategic Niche Management (SNM) (Micro-level of analysis) within the Multi-Layered Perspective (MLP) (Macro-level of analysis) in combination with the methodological approach Event Sequence Analysis (ESA). Through the theoretical and methodological exploration of chapter 2 and 3, respectively, SQ 1 and SQ 2 were answered with the chosen theoretical (MLP and SNM) and methodological (ESA) approaches. Through the ESA in chapter 4, the hydrogen transition was analyzed in order to answer SQ 3 and SQ 4. In order to answer these questions, the most 'relevant events' were mapped, analyzed and validated through three interviews with sector-specific experts. This resulted in the uncovering of 'key events' which were used to uncover the barriers that have slowed down (and still are slowing down) the transition. These barriers were always cross-referenced and backed by multiple findings from different sources.

For the SNM analysis (Chapter 5), the same event maps were used as primary data, with validation from interviews, to answer SQ5. Important in this part of the research was the need for subjective opinions and experiences of stakeholders, rather than objective facts. Hence, it was pivotal that interviews and (subjective) statements were gathered from online sources (to also prevent forwards (of backward) Bias). By revisiting the main RQ, it can be answered by taking into account the conclusions of both the ESA and the SNM analyses. The main obstacles in the ESA analysis identified technical and financial barriers, which slow down the uptake of hydrogen, which is mutually blocking internal niche process performance (vice versa). The SNM analyses how the implementation of hydrogen was handled and identifies the pitfalls/shortcomings in the past and how that effects the current expectations from different stakeholders. Even though the niche processes have performed quite well from a van der Laak (2007) perspective, there are still some improvements necessary, as well as the sheer infancy of the transition, which leads to a lack of relevant data for the SNM analysis. It is pivotal to take past shortcomings - which have shaped current expectations of all stakeholders - into account and take that as the starting point for any future development.

7.1 Answers to the Research Questions

7.1.1 Sub-Questions

SQ1	***"What are criteria for good hydrogen niche development over time?"***

From an extensive literature it was uncovered that transitions theory offers a good framework from measuring the progression of hydrogen niches across time. Stemming from transitions theory, an entrenched framework of the Multi-Level Perspective (MLP) and Strategic Niche Management (SNM) criteria arose for the assessment of hydrogen niche development. Firstly, the MLP focuses on synergistic pressures from three different levels (Landscape, Regime and Niche), which can provide windows of opportunity for niche implementation, due to pressure from the Landscape on the regime, through internal regime tensions or because the bottom-up niche offers a good solution.

The SNM framework, puts a theoretical emphasis on the optimal way of implementing such innovative niches and facilitating their growth to destabilize regimes. The SNM literature contains criteria for optimal implementation to grow such niches; Criteria stemming mainly from the v.d. Laak (2007) were used for this thesis, which put a theoretical emphasis on small-scale experimentation with a focus on assessing the quality of three internal niche processes (Voicing of Expectations, Network Building and Learning Processes) that re-enforce and influence each other. The criteria state that Expectations should be supported by an increasing number of actors, they should become clearer and more specific and they should be supported by sufficient evidence over time. The actor network should increase in diversity and alignment due to successive experimentation. Lastly, more data should be assimilated (through experimentation) to further optimize implementation (first-order learning) and actors should show enough flexibility to modify their underlying assumption regarding the niche over time, when faced with supporting evidence (second-order learning).

Finally, the hydrogen transition is unique, since it is predicated on the implementation of a number of different niches within four different sectors (Mobility, Electricity, Built-Environment and Industry), that are all related to different Socio-Technical Regimes. Because of the large-scale nature, there is a dependence on synergistic effects from implementation in different sectors, with a needed emphasis on regional consideration (cluster formation). The different niches could nevertheless be delineated to fit into a singular innovation system through a proposed TIS framework from Markard & Truffer (2009), which has guided the research by allowing for an extra emphasis on assessing the internal niche processes with inter- and intra-sector considerations with the necessary focus on clusters.

SQ2	***"How can the progress of the hydrogen niches and the emerging transition be studied over time?"***

Due to the complexity of hydrogen as an energy carrier, mainly attributed to its multiple production methods and applications within four different sectors, analysis of the hydrogen transition pathway becomes difficult. The traditional use of transitions theory has methodological shortcomings, due to its embeddedness within the multivariate perspective (with interviews as primary data), that inhibits the study of such a comprehensive transition across a long time-span, due to its focus on momentary snapshot within singular domains. Because of this, it was necessary to merge the theory with a methodological approach previously never used together, which enables examination of the entire transition with detailed analysis of how it has developed over time. The approach, 'Event Sequence Analysis' (ESA) stems from the process perspective, which views reality as a 'stream of events' without the need for "stable entities". ESA has provided specific rigorous tools and a data collection process that allowed for the analysis of the entire hydrogen transition from a long-term historical perspective, through assessment of linkages between the most relevant events and visualization of these in a so-called "event map".

Due to the focus on linkages and the visualization tool, it has become possible to analyze the implementation of different hydrogen niches within all four relevant sectors and how they affect the transition pathway across sectors. Through the merging of the ESA methodology with criteria stemming from SNM (and MLP), the progress of the hydrogen niches could be analyzed across two decades (2000 – 2020).Because primary data collection is done through historical database searches, instead of interviews, it has become possible to cross-reference data that spans back decades, nevertheless, this also makes ESA quite data-intensive. The merging of ESA with SNM provides additional benefits. Firstly, the importance of timing of certain 'Events' (experiments, voicing of expectations, formulation of visions, etc.) in ESA had great alignment with SNM theory with regards to the analysis of the internal Niche processes. The process perspective indicates: "Extremely minor events can have a large consequence because of their location in a sequence" (Spekkink, 2014). This is in line with what is stated in by Turnheima and Geels (2019) with regards to SNM: "particularly influential projects (which we call 'landmark projects') can be decisively accelerate innovation developments." Secondly, ESA includes 'unplanned events' instead of just 'planned, well-ordered and consensual management processes', with which SNM is often criticized (Farla et al., 2012). Finally, the methodology is well-suited to take outside influences into account (Boons, et al., 2014), which fits well with MLP.

SQ3	***"How did the hydrogen niches and the emerging transition evolve over time?"***

From the ESA, it has become clear that Landscape events have been highly influential in moving the niche implementation forwards by applying top-down destabilizing pressure on the regime. These landscape shifts can roughly be split into two different periods, which showcase distinct characteristics.

- **2000 – 2013:** The first period (2000 – 2013) was initiated by the 9/11 attacks in the US in 2001, which essentially sparked the entire modern hydrogen transition towards its potential as an all-encompassing energy carrier that could conceivably make the western world more independent from OPEC, with the US president coining it the "freedom Fuel" in 2003. The US' investment in the fuel directly led to an increase of attention towards the energy carrier in Europe (and the Netherlands), which sparked an initial development of the hydrogen niche in the Netherlands between 2000 and 2008, with practical experimentation mostly in the mobility sector and some feasibility studies in the Energy and Industry sectors. In 2008, in the aftermath of the economic crisis, the expectation arose that the niche was too expensive and underdeveloped, causing a kind of wave movement with fluctuations in subsidy flows, which stopped most of the experimentation between 2009 and 2012.
- **2013 – 2020:** The second period (2013 – 2020) is characterized by the climate movement, with multiple landscape events that directly led to more hydrogen uptake in all of the relevant sectors. The increased climate pressure, first from the SER accord (2013), then from the Paris Climate Agreement (2015) and towards the Dutch draft climate agreement (2019) has led to multiple openings due to the pressure on the established Oil and Gas regime. Furthermore, the energy transition also saw the rise of influential parallel niches, most notably, the Dutch opting for off-shore wind as a main renewable energy source, which combines well with hydrogen. Due to these openings, while still moderate, this period saw an increase in practical experimentation, with the most in-field projects in the mobility sector and a plethora of feasibility studies and plans in the energy and industry sector.

While the practical experimentation has been limited, the internal niche processes can be considered of high quality, which has led the country to be one of the front-runners worldwide. It is mostly due to the large-scale nature and financial barriers that this experimentation has been moderate. Due to the country's early and clear voicing of positive expectations, especially in the Northern Netherlands (which is most affected by the landscape pressure on the gas regime), the country has positioned itself as a European hydrogen hub. This positioning is a consequence of early experimentation, leading back to 2003, with high-quality learning processes that have been integrated in successive events and due to a broad actor network with diverse stakeholders that are open to collaboration and are involved in multiple projects across the country in large consortia. This lateral sharing of information not only extends across inter-sector projects, but also crosses among the different sectors, leading to more optimized implementation.

Despite the high-quality internal niche processes across the board, implementation has been moderate due to the financial barriers that comes with it, which can be attributed to the sheer expense of projects due to the niches' infancy, the large-scale nature of the transition, with the infrastructural overhaul that needs to take place and some current legislative limitations, such as sub-optimal directives towards hydrogen-grid mixing. Furthermore, there are still some pivotal misalignments in expectations between the government and industrial parties surrounding the amount and type of subsidy that should be awarded to blue- and green hydrogen projects. Furthermore, there is still some regulatory unclarity which is causing internal misalignments between actors, which in turn is causing actors to be hesitant to become involved with the niche. Finally, due to a lack of experimentation, learning processes are still in an early phase and need improvement.

SQ4	***"What patterns can be identified in the hydrogen niches?"***

As answered in SQ3, there is clear connection between the three different levels of the MLP; throughout the event descriptions, there are instances of windows of opportunities directly stem from a regime internal pressure. Next to this, there are three apparent patterns that can be identified: (1) A clear succession of niches, (2) a dependence on international collaboration and (3) regional embedding (cluster formation).

1. **Succession of Niches:** The first clear pattern that follows from the ESA is that there are clear links between successive events. This has been successfully linked to the SNM theory with the general conclusion that the hydrogen niche has performed exceptionally from an internal niche perspective. Successive projects have perpetually been influenced by positive expectations stemming from previous success stories or are facilitated by previously established collaboration. Furthermore, there are lateral links between projects, which makes it possible for learning processes to the implemented in successive events, which further optimized implementation. This good niche performance (in addition to landscape and regime influences, as well as favorable conditions), has led the Netherlands – especially North-Netherlands – to be one of the front-runners when it comes to hydrogen implementation.
2. **International Collaboraion:** Another emerging pattern has been the clear dependence on international collaboration. Particularly within the mobility sector, most niche implementations are embedded within international (mostly European) initiatives and projects or have been subsidized by them. While it is most apparent in the mobility sector, this can be attributed to the fact that this is the sector where most in-field projects have emerged. This dependence can also be observed in the Energy and Industry sectors, where the most influential developments, e.g. the construction of the first electrolyser (HyStock) or the Northern Netherlands' position as European hydrogen hub, have been influenced tremendously by European influence (particularly in the form of subsidies).
3. **Regional embedding (Cluster formation):** A final pattern is the regional embedding of the implementation of most of the niches. This can be attributed to the large-scale nature of the transition and the dependence on synergistic implementations with dependence on supply to multiple sectors. Therefore, it is most apparent in the Energy and Industry sectors, with a focus on implementations with the Northern Netherlands and South-Holland, with the benefits that come along with their big industrial clusters situated near the harbor. The unique selling point for the Northern Netherlands cluster stemmed from the proximity of all the onshore and offshore gas fields and in the South-Holland cluster the presence of the port of Rotterdam was a plus for sales opportunities for CO_2 by ship. Within these clusters is where most of the Energy sector and Industry sector activities arise.

SQ5	***"How can the emerging hydrogen transition be stimulated?"***

From the ESA it has become clear that the hydrogen transition is complex and needs active stimulation to become adopted more widely. Major challenges stem from financial barriers, which are attributed to the large-scale nature of the transition, as well as a suboptimal policy framework and the need for additional flanking activities. The ESA analysis has showed that (practical) niche experimentation has moved along the transition most rapidly, through first-order learning, by the uncovering of new unsolved questions, what the optimal policy framework would be and second-order learning, which showed entirely new application possibilities, which were previously undiscovered. Due to the infancy of the hydrogen transition, the further adoption of the energy carrier in the Netherlands in all relevant sectors should be stimulated by the continued niche implementation and upscaling. There is still a lack of financial subsidy from the government, which should be sorted out before the SDE++ will become official, which requires more interaction between the government and sectoral parties (most notably those within the industry sector).

Furthermore, the regulatory barriers can be solved in the short-term, and the government should interact with more actors to improve the policy framework barriers that are currently inhibiting practical experimentation and implementation. Even though the quality of the internal niche processes is high, one main barrier is that, even though the government expressed positive expectations, there was still a lack of practical policy framework, which is slowing down progress. So, the upscaling should be pursued with three main aspects in mind. (1) Firstly, it should be done within embedded regions, which are mainly formed in (harbor) clusters, which can promote the adoption of the niche within different sectors through strategic collaboration. (2) Secondly, the ESA proved that international collaboration is of essence in this transition, due to the large-scale nature and the need for international (mainly European) subsidy and collaboration to share learning processes and gain the appropriate network building. (3) Lastly, there should initially be a concrete focus on knowledge creation, due to the complexity of the transition, there is still a lack of knowledge with regard to the optimal implementation and a lack of educated personnel, which will all be pivotal for the success of this transition.

7.1.2 Research Question

RQ	***"How has the hydrogen niche been developing in the Netherlands, and how can this be facilitated?"***

From the research that was based on the sub questions, the research question can be concisely answered with reference to the entire body of the thesis.

The Netherlands is historically one of the major producers of grey hydrogen (second largest in Europe), which has been used in its large petrochemical industry, mainly in the industrial clusters. From the ESA (Figure 4.8) it becomes clear that the Landscape has had the most influence on the large-scale attention (studies and (practical) experimentation) towards sustainable forms of hydrogen in sectors other than industry. As the need for independence of OPEC rose with the 9-11-2001 attack in the US, a new role was assigned to the energy carrier due to its multifaceted nature and potential to make multiple sector sustainable. Due to the increased European attention towards hydrogen, this extended towards the first studies and experimentation in the early 2000s. In the energy sector and industry sector, the first studies arose in 2002 (Gasunie), but due to the large-scale nature, developments remained in-the-lab for an extended amount of time (until 2013). In the mobility sector is where the most practical niche experimentation has taken place, starting with the CUTE project in 2003. Although internal niche processes were performing quite well in the period between 2000 and 2008, the technology and socio-technical framework in which the implementation was embedded, were still very novel, which made them relatively expensive and brought technical shortcomings with them (most notably the short life-span of fuel cells). These negative expectations, along with a global economic crisis caused subsidy flows to dwindle and ceased most hydrogen experimentation between 2008 and 2012.

After the initiation of the climate movement in 2013, characterized by the signing of the SER-accord in the Netherlands, experimentation with sustainable hydrogen increased exponentially in all sectors. Most notable were the Landscape tensions on Northern-Netherlands due to the dwindling oil and gas market and the pressure from the government of the closing of the Natural gas supply in the region ("Gaskraan"). This, next to the favorable conditions in the region, created openings for the hydrogen niche to be promoted in the area. These favorable conditions were a consequence of the good internal niche performance, from voicing of positive expectation, to the attraction of the right actor-network and adequate learning processes which were undergone prior to the climate movement. This put the region in a position to receive the largest European fund to become a European hydrogen hub, which has also led to the development of the first 1 MW electrolysis factory in the Netherlands. Also, in the mobility sector, the implementation of hydrogen buses has shown good internal niche performance after 2013, which has pushed forward additional implementation. Most notably, after 2015 (after the Paris Climate Agreement) the influx in each of the sectors increased once more, with simultaneous bus implementations in different regions across the Netherlands and multiple plans for large-scale blue and green hydrogen popping up within the North-Netherlands and South-Holland clusters. Nevertheless, these plans either still need investment decisions or remained feasibility studies, mainly due to financial barriers, which stem from the large-scale nature of the transition and legislative shortcomings (sub-optimal policy framework).

Next the internal niche processes moving the transition forward, Regime and parallel-niche developments were also pivotal in the transition pathway. Firstly, in Northern-Netherlands, the set-up of “Energy Valley” proved to be highly influential for creating the preferable conditions for hydrogen in that area. Furthermore, arguably the most influential parallel niche was the Netherlands’ commitment towards off-shore wind expansion within their climate act, which would land in the industrial areas where hydrogen could serve its system function through power-to-gas storage from flexibility. Another highly influential parallel niche was that of CCS, which mainly developed in the early 2000s, which created an opening for the promotion of blue hydrogen. From the perspective of the internal niche processes (Voicing of expectations, Network Building and Learning Processes), it can be concluded that they of all been of high quality throughout the entire transition. These have pushed forward the experimentation through a broad actor network that is willing to laterally share information that was gathered through optimal first- and second-order learning processes and through the voicing of positive expectations from ‘success stories’ through the two decades (2000 – 2020), which have been backed by sufficient evidence, the expectations have aligned and have become shared by a broad range of actors. Nevertheless, some barriers have been found that are currently, particularly misalignments in expectations between the government and industry and energy sector actors which is inhibiting the roll-out of ambitious progress (subsidy discussion), as well as actors being hesitant to join the niche and start experimenting, due to unclear regulations and responsibilities. So, while the government has expressed positive expectations, it is pivotal for this to become concrete regulations.

Finally, since the niches are still in a very early stage, it is essential that actors continue to focus on niche implementations, preferably through practical experimentation. This should be done with a focus on (1) international collaboration, particularly with the European Commission, (2) regional embedding, particularly with a focus on the industrial clusters due to the synergies that can take place there and finally (3) with the main goal of knowledge creation. Simultaneously, it is the Dutch government’s responsibility to provide the optimal regulatory frameworks, which will become clear through experimentation, and finally, all relevant actors should provide supporting and flanking activities, including certification of hydrogen and creation/implementation of internationally accepted standards to further encourage collaboration.

7.2 Recommendations

This thesis found that the Netherlands has numerous sector-specific (ESA) and internal niche (SNM) obstacles to overcome. Due to the sheer scale, it is strongly recommended that the relevant stakeholders address both barrier types simultaneously, since they mutually re-enforce each other. Ideally, (the government of) the Netherlands should try to address all of the identified obstacles from the ESA as well as the SNM analyses. In practice, these obstacles – especially from the SNM analysis – are usually deeply embedded within the governmental structure of the country. Therefore, the sector-specific barriers can be addressed first, while resources are invested in conducting in-depth research into the proper way of combatting the SNM barriers that the Netherlands faces. As discussed in Section 6.3.2 and Figure 6.1 this thesis helps guide the key implications towards optimal future governmental policy. As discussed in the research question, practical experimentation should remain priority number one, while the relevant actors focus on (1) international collaboration, (2) regional embedding and (3) knowledge creation.

7.3 Future Research

This research provided useful findings, especially when it comes to identifying key events within the Dutch hydrogen transition and how this has influenced and, most importantly, hindered the transition. Yet, due to the complexity of some of these barriers (amount of mixing, hydrogen as a green fuel), due to time constraints, this thesis could not give concrete recommendations on specific actions to take. Further longitudinal research into overcoming these specific barriers is necessary. When looking at the results of Chapter 4, most of these issues, especially 'financial barriers' can be subject to further (longitudinal research). From the Sector-specific Barriers, within the 'Technical Barriers' branch, most of the technical issues have been solved throughout the ESA. Currently there seem to be no financial obstacles (theoretically). The only necessity is for more experimentation (learning processes), which should lead to practical validation and optimization. Within the 'Financial Barriers' Branch, however, there are a plethora of barriers for which currently no solution exists. Particularly the legislative limitations should be addressed in a timely manner, hence all six of those subbranches should be further considered and provided with a solution.

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Appendix A

List of Stakeholders

Table B.3 provides an overview of active stakeholders belonging to different types. The organizations in the table are reflected in the overview of initiatives, plans and applications in the previous chapters. Organizations are classified under a single stakeholder category, although some may fit under multiple kinds.

Table A.1: Overview of active stakeholders belonging to different types

Stakeholders Type	**Organizations**
Hydrogen producers and distributors	Air Liquide, Air Products, Hygear, Linde Group, Holthausen
Energy and fuel suppliers	BP, ENECO, ENGIE, Gasterra, NOGEPA, Nuon/Vattenfall, Shell, Statoil, TAQA, Total, Uniper
Energy network companies	Alliander/Liander, Gasunie (Transport Services, Energystock, New Energy), Netbeheer Nederland, Stedin/Joulz, TenneT
Vehicle manufacturers and suppliers	*Passenger Cars:* Audi, BMW Group, Daimler, General Motors, Honda, Hyundai, Pon Holding, ToyotaBuses, *Trucks:* DAF Trucks, VDL Bus & Coach, E-trucks Europe, Hymove, Scania *Other:* RAI, AutomotiveNL, Hyster-Yale
Producers of other vehicles, vessels, etc.	*Trains:* Alstom *Aggregates:* Bredenoord, Cikam, Wolter & Dros
Operators of filling stations/charging infrastructure	Allego, BOVAG, Green Planet, GP Groot, Pitpoint, Shell, Van Peperstraten (Greenpoint), Van Tilburg Bastianen, WaterstofNet
Operators of filling stations / charging infrastructure	Allego, BOVAG, Green Planet, GP Groot, Pitpoint, Shell, Van Peperstraten (Greenpoint), Van Tilburg Bastianen, WaterstofNet
Chemical and steel industry	AkzoNobel, BASF, Dow, ICL-IP, OCI Nitrogen, Proton Ventures, Shell, SynGasChem, Tata Steel, VOPAK, Yara
Technology developers and suppliers	Accenda, Ampleon, CarbonOro, CGI, Composite Agency, Coval Energy, Frames Energy Systems, Fujifilm, H2Fuel Systems, HyET Hydrogen, Hydron Energy, Hygear, Lagerweij, MTSA Technopower, Nedstack, Process Design Center, RESATO, Siemens, Tiels-Tech

Universities, research and consultancy firms	Adviescommissie Elektrochemische Conversie en Materialen (ECCM), Alterra, Arcadis, Berenschot, CE Delft, DIFFER, DNV GL, ECN, Energy Academy Europe, Energy Delta Institute, EnTranCe, Hanzehogeschool Groningen, Hogeschool Arnhem Nijmegen, Infram, ISPT, KIWA, RU Groningen, Solliance, SWECO, TNO, TU Delft, TU Eindhoven, Wageningen UR, UvA, ULeiden, UTwente
Mobility and transport users	*Public transport:* Connexxion, Qbuzz, RET, Syntus *Waste collectors:* Baetsen Groep, Cure Afvalbeheer, HVC, Suez *Vessels:* Lovers, Nedcargo, Private Transport Coöperatie Overig: Bovemij, Drone Hub GAE, Q-Park
Built environment	Ressort Wonen
Water sector	Allied Waters, Avecom, KWR, Volker Wessels, Waternet, Waterschap Rijn en IJssel
Biomass (residual flows) sector	Attero, AVR, Dutch Torrefaction Association, Biolake, Cra-W, Mestverwerking Friesland, Topell Energy, TorrCoal Technology
Government	Ministerie van Economische Zaken & Klimaat, Ministerie van Infrastructuur & Waterstaat, Rijkswaterstaat, Energiebeheer Nederland
Provinces and municipalities	Drenthe, Friesland, Gelderland, Groningen, Zeeland, Noord-Brabant, Noord- Holland, Zuid-Holland; Amsterdam, Arnhem, Breda, Duiven, Goeree Overflakkee, Groningen, Helmond, Rotterdam; Ontwikkelingsbedrijf Noord-Holland
Port companies	Havenbedrijf Rotterdam, Groningen Seaports, Havenbedrijf Amsterdam, Zeeland Seaports
Regional organizations, platforms	Amsterdam Economic Board, Deltalinqs, Energy Expo, Energy Valley/ New Energy Coalition, Energie Innovatie Board Zuid-Holland, H2Platform, Noordelijke Innovation Board, NWBA, Smart Delta Resources Platform, Smart Port, WaterstofNet
Project developers	Energy Matters, HYGRO
Funding agencies	FOM, NOW, RVO, STW, JU FCH (Europa), CEF
Norms and standards	NEN, Nederlands Metrologisch Instituut
Consumer (organizations)	Not actively involved
Environmental organizations	Not actively involved

Appendix B

Interview Protocol

B.1 Interviewees

Table B.1: List of Interviewees

Interviewee number	Function and associated organization
Interviewee #1	Managing Director at TKI New Gas
Interviewee #2	Consulting Manager Energy Transition at Accenture
Interviewee #3	Manager Business Strategy at Accenture (Energy transition, Hydrogen, Sector coupling)

B.2 Interview Structure

Table B.2: List of Interviewees

Introduction	**Part 1:** Explanation of thesis and reasoning for interview • Goal of the thesis • Discuss research questions • Explanation that this thesis looks specifically at the period between 2000 and 2020 for the four different sectors **Part 2:** Ask for verbal consistent to record the interview and ask if the information can be used in the thesis.
Map Validation	**Part 1:** Start by quickly going through the event map with the larger findings and asking if in general important events, projects and developments are missing for the respective sectors. **Part 2:** General questions are also asked about the transition with a focus on the sector of expertise of the interviewee.

<table>
<tr><td>Validation and future recommendations</td><td>Part 1: Questions per sector about the state of the transition at the moment and for the future:
How they see the hydrogen transition developing;
What the discussions of the various parties are about this development (expectations).
Is there an alignment between the expectations of stakeholders or does it still need to be very much discussed?
Part 2: If they believe that hydrogen should play a major role in the energy transition:
What they think should be done to facilitate this transition.</td></tr>
</table>

B.3 Interview Questions

Table B.3: Interview Questions

<table>
<tr><td>General Opener</td><td>How do you think the transition has gone so far in the Netherlands?
Follow-up question if not already answered (implicitly):
Did the various parties play a good role in this or could they have tackled this better?
Do you think this could have been done better or faster?
How did the Netherlands approach this compared to other countries?</td></tr>
<tr><td>Industry Sector Questions</td><td>Q1: Grey hydrogen from natural gas is now much cheaper than green hydrogen from electrolysis (three times cheaper). Do you see a market developing here and if so, how do you see this happening?
Follow-up question if not already answered (implicitly):
Offshore wind has been built up with the aid of extensive subsidies. Is that also necessary with hydrogen?
Grants are no longer necessary for wind ... how do you think the green hydrogen market could best be stimulated, is this through SDE ++ or something else?
Should investment first be made in blue hydrogen to create support or does this ensure saturation of the market?
Do the various market parties agree with you on this?
Q2: There is a lot of discussion about the Climate Agreement about the exact requirements for industry. Are you convinced that hydrogen will play a major role in the future of the industry? What do you think are the risks or pitfalls?
Are the market parties (as far as you know) the same?</td></tr>
</table>

<table>
<tr>
<td>Built Environment Questions</td>
<td>Q1: How do you view the hydrogen transition in the built environment?

What kind of future do you see for hydrogen in the built environment?
Are you convinced that hydrogen is the solution for the built environment?
Follow-up question if not already answered (implicitly):

Q2: My results show that few pilots have been carried out with hydrogen in the built environment.

Is this a bad sign, since many municipalities are opening up as guinea pigs to hydrogen?
Or do you think this is a good thing because a lot of tests still have to be done before it can be rolled out in practice?

Q3: What are the most important pilots that have been carried out and which ones are now being developed?

</td>
</tr>
<tr>
<td>Transport Sector Questions</td>
<td>Q1: What is your opinion of the state of hydrogen in mobility and how do you see this developing in the future?

Do you see a future for hydrogen as the main energy carrier in transport?
Follow-up question if not already answered (implicitly):

Q2: My results show that targets are often set for building hydrogen filling stations that are not met every time.

What do you think is the cause?
What consequences does this have for the hydrogen transition

</td>
</tr>
<tr>
<td>Electricity Sector Questions</td>
<td>Q1: What is your opinion about the future of P2G in the Netherlands and how do you see this developing in the future?

Do the different parties agree with you on this or do you see that the expectations of the different parties differ?
Follow-up question if not already answered (implicitly):

Q2: The Northern Netherlands is seen by several parties as a cluster with great potential to become a hydrogen (P2G) hub, especially because of the infrastructure that converges in the Northern Netherlands, the great potential for underground storage and the years of experience with gas and gas infrastructure.

Do you share this opinion?
How do you see this developing in the future

</td>
</tr>
</table>

General Concluding Question	What do you think must be done for the hydrogen transition to be successful?
	• What is the role of the various stakeholders in this
	  – Government
	  – Businesses
	  – Sectors

Appendix C

Additional Information

C.1 Methodology

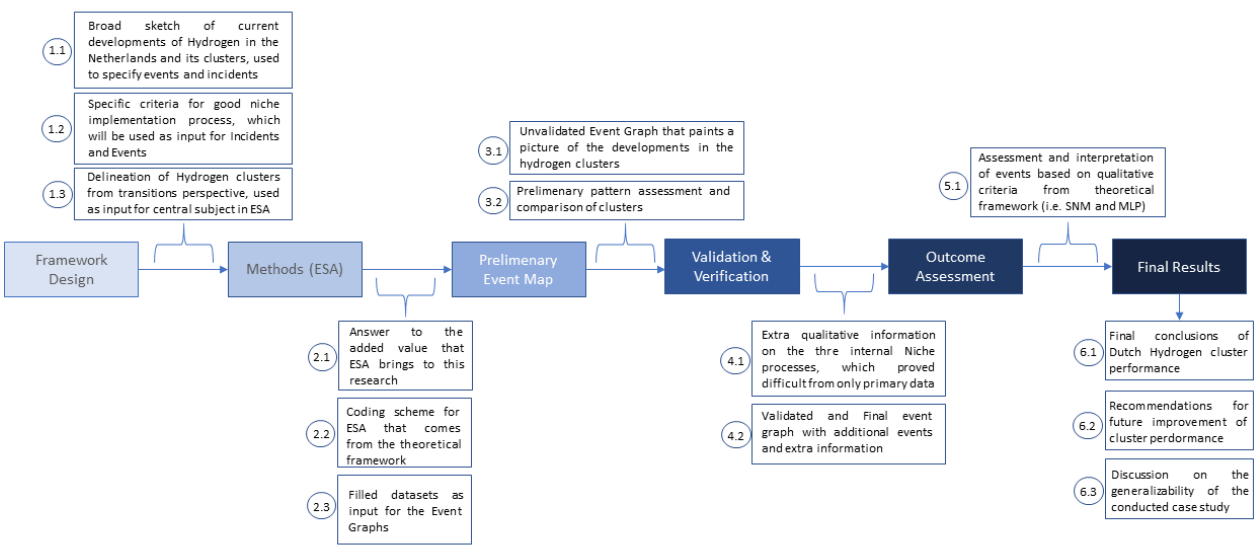

Figure C.1: Research Design: This elaborates upon the Research Approach by describing the results that come out of each of the steps and will be used as inputs for the following steps

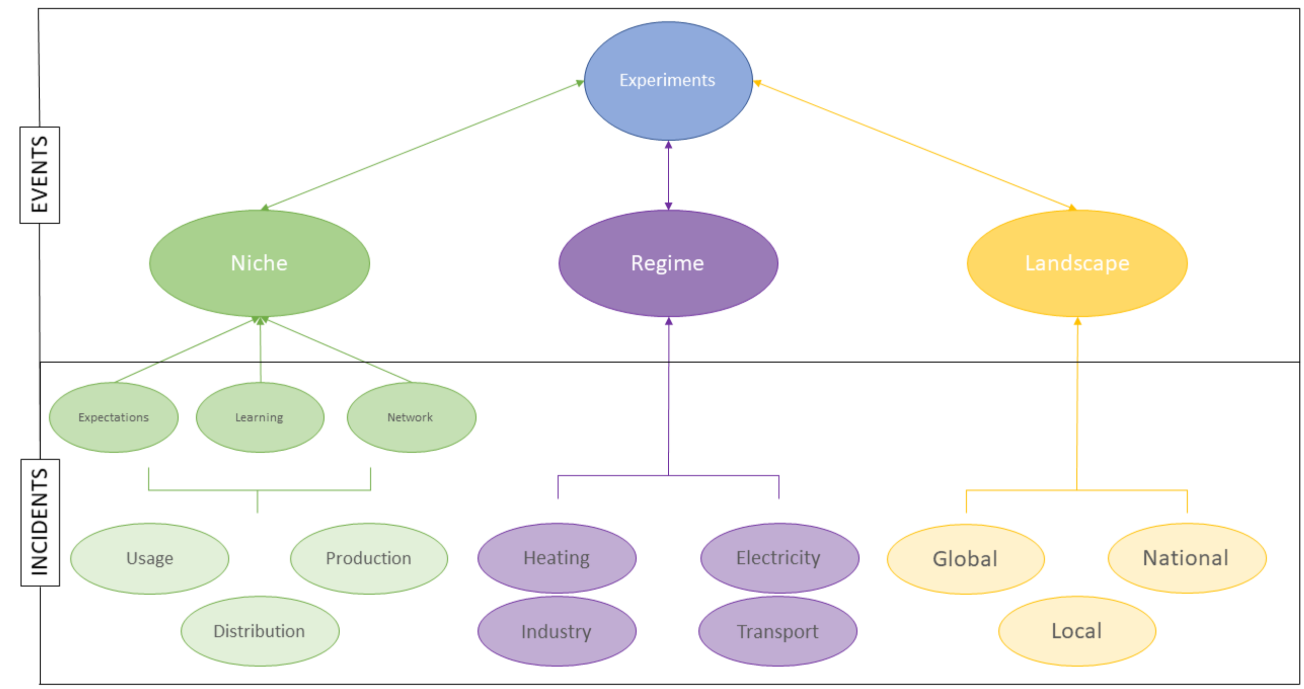

Figure C.2: Incidents and Events

C.2 Measures from the Dutch government to encourage the use of hydrogen

- The national government encourages projects to further investigate the sustainable possibilities of hydrogen and to increase the production of sustainable hydrogen. The government makes money available for this. And it is being investigated which laws and regulations must be amended.
- The national government is investigating whether the current gas network can be used for the transport of hydrogen in the future. This is especially true for the use of hydrogen in industrial areas. And for heating in the built environment.
- The 30 to 40 largest municipalities in the Netherlands are establishing a CO_2-free zone for city logistics. Electric freight traffic and hydrogen freight transport are allowed in this zone.
- The national government is working on a Hydrogen Program. This describes how the agreements and ambitions of the climate agreement can be implemented with all parties.
- The national government is working on the conditions for the international market for sustainable hydrogen. For example, the same rules, standards and safety standards for the transport, storage and use of hydrogen, and certification of green hydrogen. The government does this together with neighboring countries, the European Union and countries outside Europe.

C.3 Historical Development of Hydrogen

The first description of hydrogen is attributed to the German-Swiss scientist Philippus Aureolus van Hohenheim, better known as Paracelsus. In 1520 he described an ascending gas, which was probably hydrogen. However, he did not give it a name and did not discover anything about the properties. 1625 - Jan Baptist van Helmont is the first to reject the Aristotelian theory and use the word “gas”, which is the pronunciation of the word chaos in Dutch (source). In 1670, the English scientist Robert Boyle demonstrated that this gas is flammable in the presence of air. Nearly a hundred years later, in 1766, the Englishman Henry Cavendish recognized hydrogen as one of the elements. The French Antoine Lavoisier gave this element the name “Hydrogene,” or hydrogen, in 1781. The first use of hydrogen was in 1783 when the Frenchman Jacques Charles first took off a hot air balloon with hydrogen (instead of hot air) and in 1801 Humphry Davy demonstrates the principle of electrolysis, the splitting of water into hydrogen and oxygen, by passing a strong current through water.

The English Sir William Robert Grove invented the first fuel cell in 1842, which was the reverse principle of Davy’s electrolysis. His “gas battery” consisted of two platinum electrodes in sulfuric acid, one in contact with hydrogen gas, the other with oxygen. Although commonly referred to as the father of the fuel cell, a similar experiment with platinum, hydrogen, and oxygen had already been reported two years earlier by Swiss-German chemist Schönbein. In 1889 Charles Langer and Ludwig Mond gave the name “fuel cell” (fuel cell) to Grove’s invention. They report great difficulty controlling the liquid sulfuric acid, the “electrolyte.” Seven years later (1896), Wilhelm Oswald writes in his book “Electrochemistry, History, and Theory” that Grove’s battery has no practical use (but is theoretically relevant). From 1932, the British researcher Francis Thomas Bacon revisited the theme of fuel cells. In 1959, after years of research, he showed a 5-kW alkaline fuel cell (with alkaline electrolyte instead of sulfuric acid). In 1959 he demonstrated the application for a tractor with a 15-kW fuel cell stack with a stack of 1008 cells. Also, in the 1950s, General Electric invented the polymer-membrane fuel cell, which uses a solid membrane instead of a liquid electrolyte.

As a result of these developments, there is a broader interest in fuel cells. This leads to NASA using fuel cells in aerospace in the 1960s - Pratt & Whitney, an aircraft engine builder, had bought Bacon’s patents and won the power supply contract for the Apollo spacecraft. The fuel cells not only provided high efficiency-power, but also drinking water on board the space shuttle.

Summary of the Historical development of hydrogen (1500 - 1960)
In Figure C.3 a broad overview of the sequences of events of the historical development of hydrogen is summarized from the initiation in 1520 up to the 1960s.

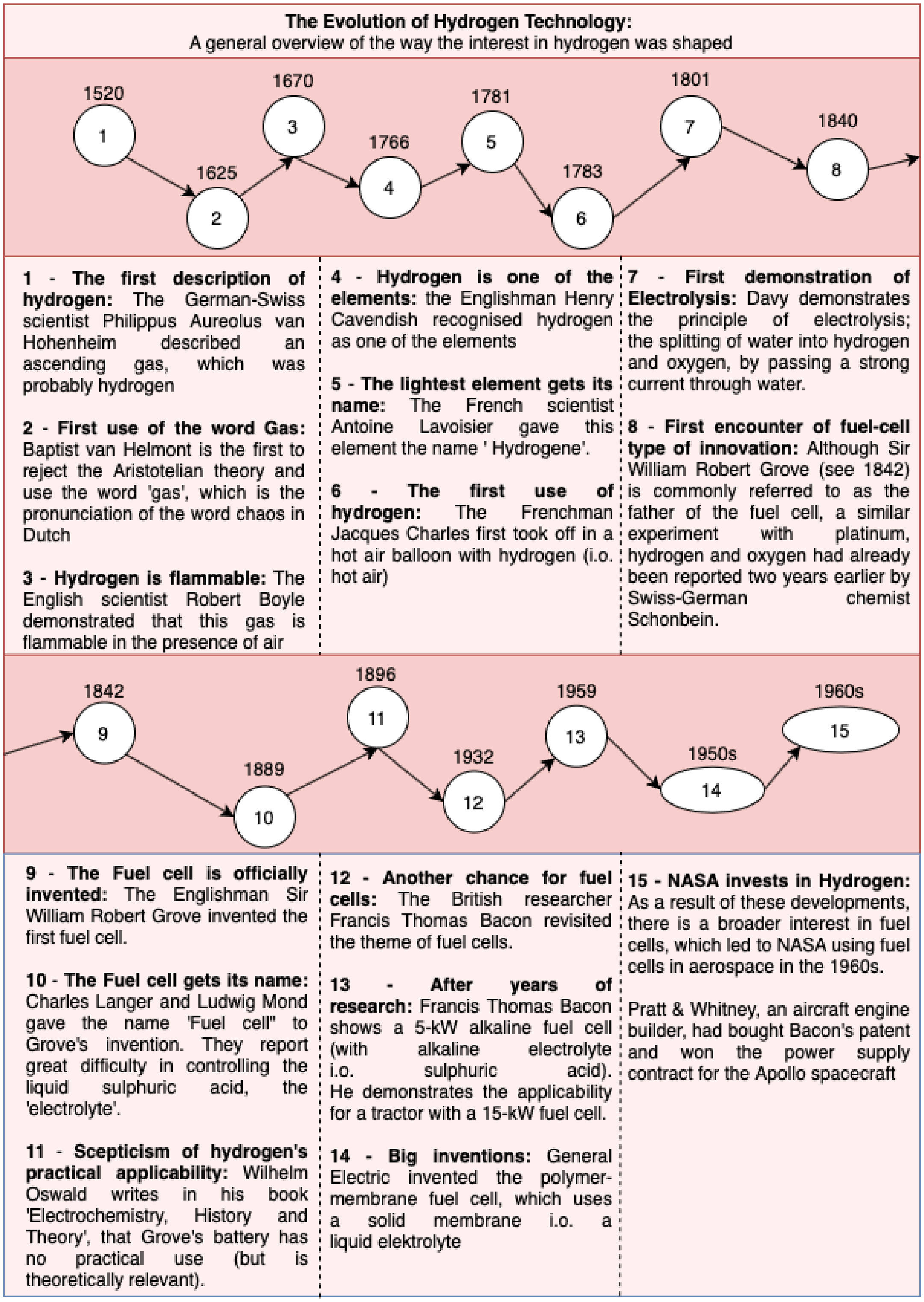

Figure C.3: The Evolution of Hydrogen Technology: A general overview of the way the interest in hydrogen was shaped

C.4 Conceptual Image

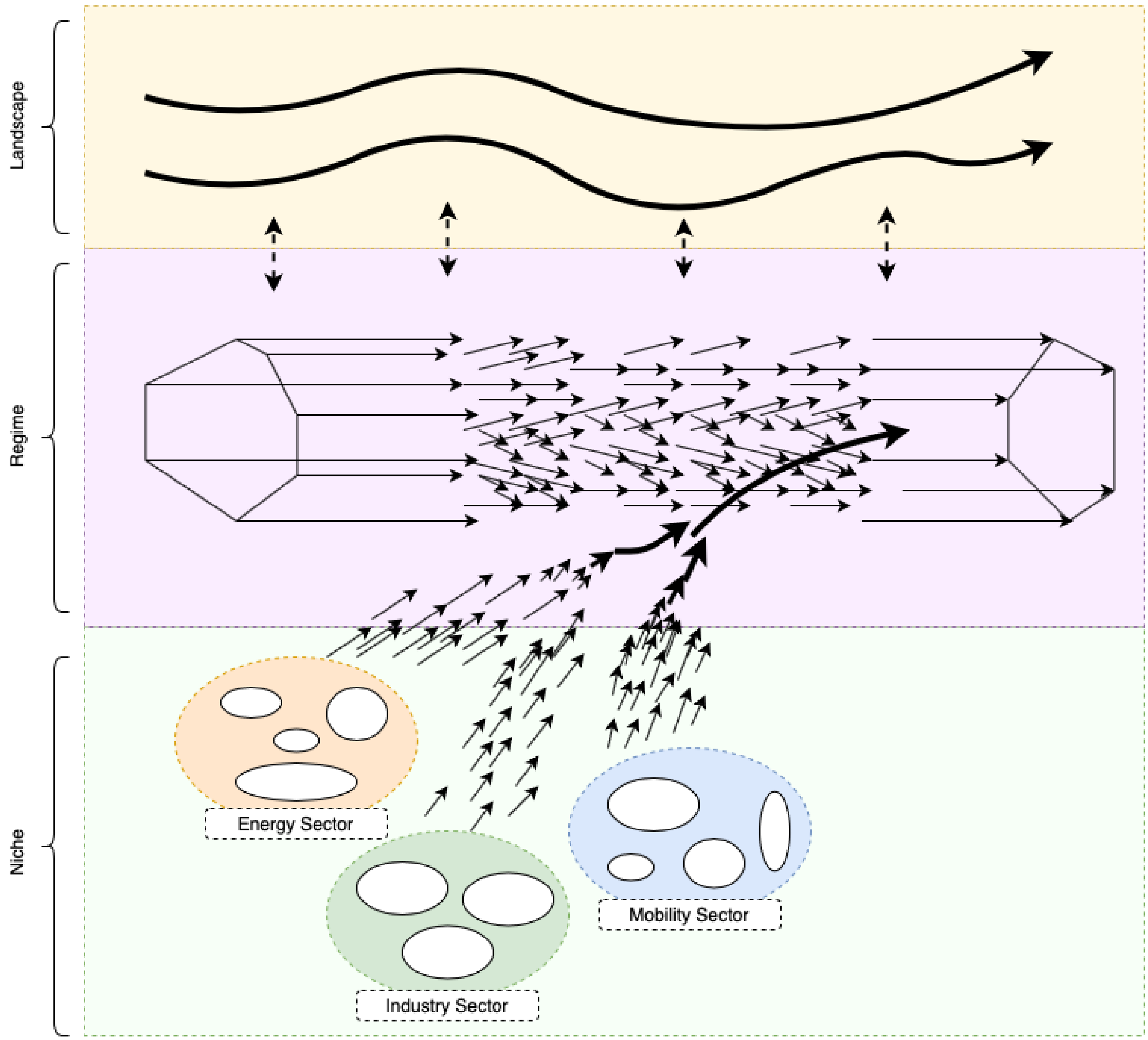

Figure C.4: MLP image which shows the importance of all sectors in order for the hydrogen niche to gain traction in regime