RESEARCH REPORT

Hydrogen energy applications for the built environment: the missing link in the energy transition?

Investigating the opportunities to bring hydrogen energy applications for the built environment from the niche to the regime level

Client: University of Groningen - Faculty of Spatial Sciences

Date: 31 December 2018

Version: Final version

0.1/Draft

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Document title:	Hydrogen energy applications: the missing link in the energy transition in the built environment? Investigating the opportunities to bring hydrogen energy applications for the built environment from the niche to the regime level
Document short title:	Hydrogen energy applications: the missing link in the energy transition in the built environment?
	0.1/Draft
Version:	Final version
Date:	31 December 2018
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Credentials of cover photo:	*Traditional and contemporary wind mills in Eemshaven , Netherlands (*D.Y. Glastra *(own work)*)

Preface

This thesis marks the end of the Master Programme Environmental and Infrastructure Planning (EIP) and, as such, the end of a very exciting, informative and enriching period of my life as well. This master programme in particular and the entire period of studying at the Faculty of Spatial Sciences and the University of Groningen in general shaped my personality. My studies and all side-activities I did in this period helped me discovering my passion to contribute to a better and more sustainable world. In other words; it provided me with a new perspective on the world.

It goes without saying that this document (and the process that established it) could never have been written and done all by myself. Therefore, I would like to make use of this opportunity to thank all those people who assisted me while writing and executing this study:

First, I would like to thank all the interview respondents, for making time in their busy agendas to conduct the interviews and for sharing their experiences and interesting, valuable and relevant information on the fields of hydrogen energy, the energy transition in the built environment and the institutional organisation of these topics in the Netherlands. Their input is the backbone of this study.

Second, I also would like to thank my family and all of my friends for the constant and unconditional support they gave me during my time as a student in Groningen. Their support was much needed from time to time, especially during the intense period in which I completed two master theses, which was not always easy and sometimes even stressful. Without their support, I probably would not be able to keep up the motivation while working on this.

Third, I would like to thank all team members of the business units of Transport & Planning and Industry & Buildings of Royal HaskoningDHV Groningen for the welcoming atmosphere at the office during my internship period and their valuable networks that brought me into contact with the interview respondents

Last but not least, I would like to give a special word of thank to dr. Ferry Van Kann, for being a helpful, motivating and inspiring supervisor, and to Marc Jager, who made me enthusiastic on the subject of this study and who gave me the opportunity to combine writing my thesis with a very informative and enriching internship at Royal HaskoningDHV. Additionally, they both stood in for professional guidance and were always willing to answer questions and to provide useful tools.

A new step in my life is ahead of me, in which I aim to use the new perspective I described above in professional practice as a consultant at Royal HaskoningDHV. I am looking forward to this new step and all the new opportunities that are ahead of me, but I am sure that I will occasionally melancholically look back to the great time I had as student at the Faculty of Spatial Sciences.

I hope you enjoy reading this research report,

Dion (D.Y.) Glastra
Groningen, December 31st, 2018

Abstract

Hydrogen energy applications could in certain situations be able to cope with the challenges involved with the energy transition in the built environment in the Netherlands. The Netherlands have an excellent existing distribution infrastructure, a lot of potential for sector coupling, and a strong intrinsic motivation to shift away from fossil fuels. These conditions are beneficial for the facilitation of hydrogen energy applications and are increasingly well recognised by different stakeholders. Actual implementation lags far behind, however.

Incorporating hydrogen energy applications requires irreversible systemic changes in the current socio-technical regime of the energy supply system. From a transition perspective, such changes could be approached from three analytical levels, of which the regime level (between the landscape and niche level) is of prime interest. By using the initiative of Nijstad-Oost/Erflanden in Hoogeveen as a case study, it is shown that this regime level in the energy transition in the built environment can be changed by coordinating, facilitating and stimulating public authorities and, as such, facilitate the implementation of hydrogen energy applications in the built environment.

To bring hydrogen energy applications for the built environment into the regime, it is argued that trust and experience with hydrogen-based energy among both stakeholders and society should increase. By conducting pilot projects, stakeholders gain experience and consequently, more exploitative stakeholders could become familiar with this sustainable innovative niche, which in turn might lead to a shift in the regime.

Therefore, it is argued that authorities need to, at the one hand, develop a clear and unambiguous vision on the energy transition in the built environment and, at the other hand, provide extensive policy space to stakeholders for executing new pilots and allow stakeholders to adopt a different role. Both national and regional coordination is necessary to ensure reflexive learning processes of diverse pilots and the development of a coherent, thought-through energy supply system for the built environment. Regional transmission system operators (TSOs) and provinces are argued to have a crucial role to coordinate the pilots and maintain alignment. TSOs for advising stakeholders and society which choices will be the most socially acceptable due to their extensive knowledge on the grid, and provinces are assumed to be a crucial facilitator to connect different alternatives and enable reflexive learning processes

Finally, a recommendation for The Netherlands is to profile itself as a frontrunner in the field of hydrogen energy to attract international publicity and to exploit its attributes that are in favour of hydrogen energy. This may result in an increase of the general awareness among stakeholders from different disciplines and an acceleration of the energy transition in the built environment in general. Such publicity might enable stakeholders to apply an explorative attitude that helps to overcome obstacles like the lack and incompatibility of the current legislative framework.

Keywords: Hydrogen energy, energy transition, built environment, regime level, transition management, multilevel governance

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List of abbreviations

BESS	Battery Electricity Storage System
BZK	Dutch Ministry of the Interior and Kingdom Relations
CAES	Compressed Air Energy Storage
CCS/CCU	Carbon Capture & Storage / Carbon Capture & Usage
CO_2	Carbon dioxide gas *(the main greenhouse gas)*
EU / EC	European Union / European Commission
EZK	Dutch Ministry of Economic Affairs and Climate Policy
FES	Flywheel Energy Storage
GSHP	Ground-Source Heat Pump
H_2	Hydrogen gas
I&W	Dutch Ministry of Infrastructure and Water Management
P2(H)G	Power-to-(Hydrogen)-Gas
PHS	Pumped Hydroelectricity Storage
SDE+	Stimulering Duurzame Energieproductie (*Dutch subsidy programme for sustainable energy generation)*
SER	Sociaal-Economische Raad *(*English*: Dutch Socio-Economic Council)*
SWOT	*(Analysis of)* Strengths, Weaknesses, Opportunities and Threats
TSO	Transmission System Operator (Dutch: *netbeheerder*)

Glossary

Built environment
In this study, the built environment is referred to as the entirety of buildings (houses, offices, public buildings, etc.) that consumes energy for other purposes than industrial production of goods, transport or energy conversion (SER, 2013; CBS, 2018a).

CCS / CCU
Carbon Capture and Storage / Carbon Capture and Usage. These are process that can be used to reduce CO_2 emissions by capturing CO_2 before or after combustion and then either store it or use it for other (industrial) purposes (Dincer & Acar, 2015; Koytsoumpa et al., 2017).

Decentralised authorities
In this study, the term 'decentralised authorities' refer to what in Dutch is called '*decentrale overheden'*; regional government authorities that have some level of autonomy with respect to energy planning. There are two levels of decentralised authorities that are relevant for this study: provinces and municipalities (CBS, 2018c).

Endothermic / exothermic
Endothermic processes are processes that necessitate a net influx of (thermal) energy. Exothermic processes release thermal energy (Mandl, 1988).

Energy carrier
An energy carrier is any phenomenon or substance that is used to transmit or transform energy from an energy source (or another energy carrier) to a consumer (based on ISO, 1997). This energy is used by the consumer as power, heat or light (while acknowledging the laws of thermodynamics). It is not necessarily an energy source.

Energy end-use sector
An energy end-use sector is a category of energy consuming entities that is distinguished by its distinctive characteristics in energy demand and energy use that set them apart. In this study, the built environment is distinguished as an energy end-use sector (based on EEA, 2013 and CBS, 2018a).

Energy/climate neutrality
Energy neutrality is a term that is popular among stakeholders in the governance of the Dutch energy transition. The term is relevant for this study, as many stakeholders in the semi-structured interviews refer to it. In that context, energy neutrality means that the total energy consumption may not involve a net emission of greenhouse gases. Measures to achieve this include both sustainable energy alternatives and insulation. Climate neutrality is a term that is not preferred for use, although it is still frequently used by respondents (based on RVO, 2018).

Energy production / generation / efficiency / storage
According to the laws of thermodynamics, energy cannot be produced, nor lost, nor wasted (Mandl, 1988). Whenever in this study these terms are referred to, the generation, storage and/or loss of practically usable energy by human action is meant.

Energy source	An energy source is any substance, force or the result thereof that can be used to produce energy carriers (while acknowledging the laws of thermodynamics) (based on ISO, 1997).
Energy supply system	In this study, an energy supply system is defined as the entire chain of generation, distribution, storage and use of energy (while acknowledging the laws of thermodynamics), as well as its associated infrastructures and institutions (based on ISO, 1997).
Energy transition	The multiple-dimension transition from fossil, exhaustible and unsustainable energy sources and carriers towards non-fossil, non-exhaustible and more sustainable energy sources and carriers. This transition involves several dimensions; the energy transition unavoidably implies a fundamental change in a) demand and supply security patterns, b) spatial generation and visibility of energy and c) increase of interdependency of all elements (WEC, 2014).
Hydrogen energy application	In this study, the term 'hydrogen energy application' refers to any practically feasible process or method to use hydrogen as an energy carrier for electricity supply, heat supply or energy storage.
Sector coupling	Within the context of the energy supply system, sector coupling is a process in which energy carriers are integrated in a system in order to use them in more than one energy end-use sector. Hydrogen is an outstanding example of such an energy carrier, as it is suitable for use in all energy end-use sectors (Clean Energy Wire, 2018).
Sustainable energy alternative	In this study, the term 'sustainable energy alternative' refers to any alternative method of energy supply to the current system (except for hydrogen energy applications) that could be considered to contribute to a sustainable energy supply system. For a definition of what is meant by sustainable energy supply, see below.
Sustainable energy supply	For this study, sustainable energy supply is defined as any energy supply system that adheres to the general sustainability definition applied by the WCED (1987): '*[energy supply] that meet the needs of the present without compromising the ability of future generations to meet their own needs.'* More specifically, it means any energy supply system that does not use fossil or nuclear energy sources and/or carriers, as well as the steps that are needed to be taken towards such a supply system.
TSO (Transmission System Operator)	In this study, the term Transmission System Operator (TSO; Dutch: netbeheerder) refers to both the national (Gasunie/TenneT) and the regional TSOs in the Netherlands. TSOs are responsible for the construction, management and maintenance of the grids for electricity and (natural) gas.

1 Introduction

'*Water will be the coal and oil of the* future'; already in 1874, Jules Verne predicted the emergence of a hydrogen-based energy supply system. After Verne, many more authors and scientists alike announced the hydrogen economy to come soon (e.g. Winsche et al., 1973; Barreto et al., 2003). So far, however, reality proved them to be wrong; hydrogen turned out to be an impractical and unfeasible energy carrier (Cherry, 2004; Hultman, 2009). Times are changing, however: both the need for and the challenges of the energy transition, combined with a sharp reduction in the costs of renewable energy might open the way to a break-through of a (partly) hydrogen-based energy supply system. For transport purposes, but also for the built environment these hydrogen energy applications have captured the attention of companies and policy makers to a much larger extent than ever before: TU Delft is experimenting with hydrogen energy for both electricity and heat supply for homes (The Green Village, 2018) and in Hoogeveen, the first neighbourhood that will be running on hydrogen energy is currently being planned (DvhN, 2018). The Netherlands, and especially the northern part of it, are hesitatingly exploring a large-scale implementation of hydrogen-based energy applications (NIB, 2017; SER, 2018). Hydrogen energy is currently amongst the most intensively studied subjects within the field of new energy supply (e.g. Hanley et al., 2017), and TSOs, energy companies and many small businesses believe in it, but the question is: are governments, companies and society ready for it?

Figure 1.1: Hydrogen energy-based home in The Green Village, a test site for innovative energy solutions in Delft. (The Green Village, 2018)

In the autumn of 2017, a visionary document has been set up by the Northern Innovation Board (a coalition of governments, research institutes and influential companies) to position the Northern Netherlands as an ideal place to start building a green hydrogen economy (NIB, 2017). Since that moment, increasing attention has been given to the possible key role of hydrogen energy in the Dutch energy transition (e.g. CE Delft, 2017; SER, 2018). These are very interesting developments within the Dutch policy arenas for sustainability in general and energy transition in particular. The decision by the Dutch government to abolish natural gas extraction in Groningen by 2030 (Rijksoverheid, 2018c) only created more urgency to find an alternative to the current fossil fuel-based energy supply system, as 98% of all Dutch households fulfilled their heat demand with natural gas (SER, 2013; Gigler & Weeda, 2018).

The underlying reason for the exploration of new energy technologies is the awareness that the current energy supply system is not sustainable on the long term (WCED, 1987): conventional energy sources are exhaustible (Shafiee & Topal, 2009), they cause climate change (IPCC, 2007), they make us dependent on countries we do not want to be dependent on (Gnansounou, 2008) and, what makes it particularly important for the Netherlands, the extraction and use of fossil energy sources cause negative local side effects such as earthquakes induced by natural gas extraction (Van der Voort & Vanclay, 2015; NAM, 2018). About 20% of all energy carrier consumption in the Netherlands is accountable to the built environment (CBS, 2018a). Therefore, society needs to find alternative technologies to fulfil heat and electricity demand in the future. Alternatives are available for a long time already, but all of them pose many challenges. Technological challenges (Kemp, 1994), but the most critical challenges are probably more of an institutional nature, which is especially true for the built environment with its extremely wide range of stakeholders (Campbell, 2006; Meadowcroft, 2009; Loorbach, 2010).

One such category of alternatives consists of hydrogen energy applications. Hydrogen energy applications have many opportunities and are therefore increasingly often considered to be a potential key component of the energy transition. Hydrogen is a robust and powerful energy carrier (Verfondern & Teodorczyk, 2007) that is able to cope with critical challenges of the energy transition (the intermittency problem being the most prominent one), it is an energy carrier suitable for sector coupling (see **Glossary**) and hydrogen has no direct local pollution effects. Additionally, hydrogen is relatively easily transportable and tradable (Gigler & Weeda, 2018). However, hydrogen energy applications also involve serious challenges to the current socio-technical system. Such changes involve the need to reconsider society's institutional framework, as it is currently not designed to cope with a hydrogen-based energy supply.

A promising and inspiring energy future might be ahead of us if society is willing and able to incorporate hydrogen energy applications into the energy transition in the built environment. This study explores how important stakeholders in this field, including regional public authorities, transmission system operators (TSOs) and companies could both stimulate society and being stimulated by society to incorporate these hydrogen energy applications into the energy transition in the built environment.

1.1 Research objectives

The developments outlined above make the Netherlands a highly relevant and interesting research context for exploring the facilitation of hydrogen energy applications for the built environment. It could be expected that this involves a complex and multi-faceted expedition (e.g. De Roo, 2003; Jordan, 2008); with so many stakeholders involved, rather small margins in terms of finance and existing energy infrastructures and institutions that could be fundamentally incompatible with some of the alternatives proposed (SER, 2013; Rijksoverheid, 2016b). Therefore, the main objective of this study is to investigate how hydrogen energy applications for the built environment in the Netherlands could be facilitated by stakeholders who have the authority and profile to do so. To achieve this objective, several issues need to be addressed:

First, the potential position of hydrogen energy applications for the built environment in a future sustainable energy supply system is to be investigated. The energy transition will likely result in a fundamentally different energy supply system, due to the increasing variation in energy supply that is inherently connected to renewable energy sources (Elzen et al., 2004; De Boer & Zuidema, 2013). Hydrogen can function as an energy carrier that is able to cope with this intermittency problem (also see **Introduction** and Section **2.1**). In addition, following from increasing spatially dispersed patterns of energy generation, the layout of the system in the built environment will also result in different options that are applied in the same time frame (Smale et al, 2011; De Boer & Zuidema, 2013). This is expected to be especially relevant for the built environment, which comprises of many stakeholders and which is subject to large variety in demand, both seasonal and daily (see Section **2.1**). Sustainable energy supply for the built environment is not just a technological challenge, however; it should be addressed as a challenge that requires changes in many systems to be successful, e.g. social acceptance by end users, updated safety standards, improved technology and redevelopment of infrastructure on all levels (Meadowcroft, 2009). To optimise efforts and reduce failures, stakeholders involved in sustainable energy supply for the built environment should use a common frame of reference for dealing with the systemic change described above. Hence, this study aims to identify the potential position of hydrogen energy applications in a future, sustainable energy supply system for the built environment. A sustainable energy supply system for the built environment is defined as '*non-fossil and non-nuclear energy alternatives for electricity supply, heat supply and energy storage in the built environment that meet the needs of the present without compromising the ability of future generations to meet their own needs* (based on WCED, 1987; also see **Glossary** and Section **3.2**).

Second, to manage the issues connected with the future energy supply for the built environment outlined above, a systemic change is required. For such change to happen, irreversible changes in the existing socio-technical energy supply system for the built environment are required (Rotmans et al., 2001; Geels, 2011). The current energy supply system for the built environment and its associated infrastructures are a result of continuous improvements to systems that were designed in the course of the past (De Boer & Zuidema, 2013) and are strongly interrelated with the growth in energy consumption, which appears to be accountable to the incorporation of fossil fuels during the course of the 19th century (also see Figure 1.2), but when the energy transition in the built environment will be completed, the energy supply system will most likely be fundamentally incompatible with the current energy supply system. Systemic change could be induced by a transition (Rotmans et al., 2001). This transition is showing its first traces of development now: physically, socially and in terms of regulations and institutions (see e.g. Rijksoverheid, 2016b and SER, 2018). For example, the obligation to connect new developments to the natural gas grid was officially abolished in July 2018 (Rijksoverheid, 2017b) and the emergence of initiatives to experiment with hydrogen energy applications (TKI Nieuw Gas, 2018) is a sign of a transition in process. However, a clear point of departure for the energy transition in the built environment is lacking so far, as is the case for the position of hydrogen energy applications in that transition (Gigler & Weeda, 2018). Therefore, this study aims to identify both the current phase of the energy transition in the built environment and the current level of development of hydrogen energy applications for the built environment.

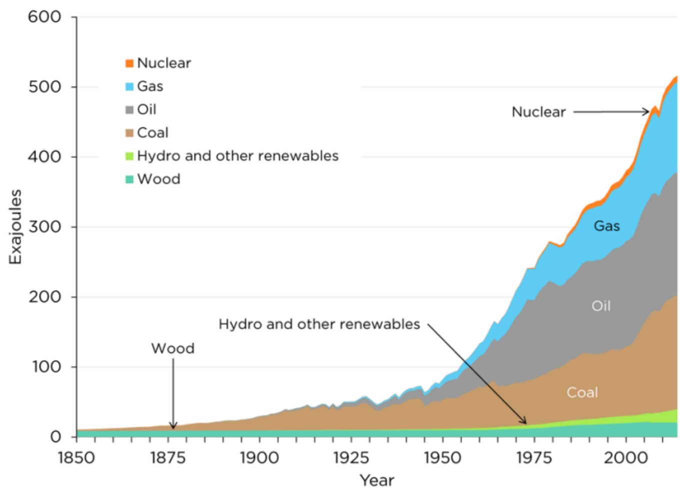


Figure 1.2. Growth of world energy consumption and share of main energy sources (Hughes, 2014).

Third, there are both opportunities and challenges involved with the implementation of hydrogen energy applications. A desire to fundamentally change the energy supply system for the built environment creates problems and involves challenges, as security of supply, safety and efficiency should be ensured (Duit & Galaz, 2008; Winzer, 2012). A lot of investments and societal costs are involved with adaptation and drastic spatial and institutional changes will be necessary (Kemp, 1994). However, hydrogen energy applications might involve less drastic changes than other alternatives and are therefore a potentially very promising alternative (Gigler & Weeda, 2018). As a result, several governance challenges are experienced and to be expected with regard to exploring the potential of hydrogen energy applications in the energy transition in the built environment (Elzen et al, 2004). Currently, there is no stable institutional design or coordination on which stakeholders are involved; neither there is a wide awareness on the opportunities hydrogen-based energy might offer. Stakeholder involvement and participation is needed to solve such barriers to hydrogen energy applications in the energy transition in the built environment. However, the involvement of stakeholders and society seems to be a challenge (Van der Brugge et al., 2005; Geels, 2011); stakeholders are interest-driven and their interests are widely different among stakeholders, which hampers the desired collaboration (Elzen et al., 2004). In addition, society has a sceptical attitude towards hydrogen in its broadest sense (Gigler & Weeda, 2018) but acceptance is argued to be necessary to enhance support for the (eventual) implementation of such new developments in the energy supply system for the built environment (Kemp & Rotmans, 2004). In addition, struggles are expected to be found particularly on the lower scale levels. Currently, both the national and provincial governments put the responsibility to initiate the energy transition in the built environment at the municipalities, e.g. by the Environmental Act that is going to be implemented in 2021 (Rijksoverheid, 2018d). Although the municipality is supposed to have the knowledge on what their specific neighbourhoods and villages look like and their citizens are likely to get more influence on their environments, there is also a dilemma to this development (Needham, 2005). It is difficult to expect that (in particular) relatively small municipalities, let alone single citizens, have enough expert knowledge, capacity, willingness and resources to deal with the uncertainty that is involved with a transition a complex context (Gupta, 2007; Zuidema, 2016; see Section **3.5**). Therefore, bottlenecks could emerge in this energy transition in the built environment, as these niche developments are considered *'the seeds for a transition'* (Elzen et al., 2004, p.253). Hence, this study aims at providing an overview of the different opportunities and challenges to the facilitation of hydrogen energy applications for the built environment.

Fourth, to be able to facilitate hydrogen energy applications in the built environment, it is necessary to identify the stakeholders who are responsible for planning the energy supply system in the built environment and their respective roles. The existing socio-technical system has been firmly embedded in society for decades and emerged slowly over the years (Duit & Galaz, 2008). This resulted in a governance system that fits such a system and in which stakeholders have a clear role (Geels & Kemp, 2000; Van der Brugge et al, 2005). In an energy supply system under transition, however, the roles of stakeholders might not fit with the objectives of the system anymore (Duit & Galaz, 2008; Winzer, 2012). Stakeholders have to act within the (legislative and regulatory) boundaries of this socio-technical system, and changing that happens only slowly (Meadowcroft, 2009; Edquist, 2013, also see Section **3.3**). In this study, the stakeholders who have the task to manage the energy supply system are referred to as the regime level stakeholders (following Geels & Kemp, 2001; Rotmans et al, 2001; Van der Brugge et al, 2005). The regime level comprises the stakeholders that can facilitate and foster changes and can therefore be considered the most important level of a transition (Geels, 2011). These regime level stakeholders, which include governments, public authorities and companies, usually motivate their decision on a financial base (just like households do) and have a '*vested interest in the existing system and invest [only in] innovations [that] improve its performance*' (Elzen et al., 2004, p.252). These stakeholders can foster actual societal change (Geels, 2011). At the regime level, institutions and regulations are designed to guide public and private action (Rotmans et al., 2001) (see Sections **3.3** to **3.5**). For the energy transition in the built environment, these activities seem to correspond with the responsibilities of all government levels in the Dutch planning system, which causes the governance context of the energy transition in the built environment to be a rather complex context in which it is unclear what the responsibilities of the different stakeholders are. This study is focused on identifying these stakeholders, who both strive to exploit the current system and to explore alternatives to it that could improve the system, as well as on providing insights in the different roles of these stakeholders.

Fifth, it is necessary to investigate how and by whom regime level stakeholders can be influenced and changed. From a transition theory perspective, landscape level stakeholders can do so by executing strategic activities, for example the EU who formulates long-term visions that consequently are being translated into concrete policy (European Commission, 2010; Loorbach, 2010). Operational activities from the niche level stakeholders are also argued to affect the behaviour of regime level stakeholders (Loorbach, 2010; Geels, 2011). Such operational activities include sustainable innovative niche development (Geels & Schot, 2007; Caniëls & Romijn, 2008). Sustainable innovative niches are then argued to undergo a process of diffusion of innovations before becoming part of the transition arena in which sustainable innovative niches try to infiltrate in the existing energy supply system for the built environment (Geels, 2011; Rotmans et al., 2001; Rogers, 2010; Walsh, 2012; also see Section **3.1** and **3.2**). In that context, the opportunities and challenges related to these sustainable innovative niches become important (Kemp & Rotmans, 2004, Duit & Galaz, 2008). To study how these struggles can be governed in the complex context in which the energy transition in the built environment takes place, transition management theory can offer a useful tool (Loorbach, 2010; Geels, 2011) (also see Section **3.5**). Hence, this study aims to unravel how stakeholders at the regime level are being influenced and changed in relation to sustainable innovative niche development.

Last, when the five issues above have been addressed, the findings could be combined to develop a conceptual framework on the governance of facilitating hydrogen energy applications in the built environment. This framework aims to operationalise the opportunities and challenges related to hydrogen energy applications for the built environment, specifically for the governance context of the energy transition in the built environment in the Netherlands. This is relevant, because opportunities and challenges are always perceived as such by stakeholders, and that determines how they consequently act with regard to hydrogen energy applications in the built environment. Like it has been outlined before, the biggest challenges towards the implementation of niche developments are probably socio-institutional rather than technological (Campbell, 2006; Meadowcroft, 2009; Loorbach, 2010).

1.2 Research questions

In short, this study focuses on these governance aspects and dilemmas in relation to the responsibilities of stakeholders at the regime level with regard to exploring the potential of hydrogen energy applications in the energy supply system for the built environment, which is currently under transition in the Netherlands. The main research question that is being answered in this study therefore is:

How could hydrogen energy applications for the built environment be facilitated by regime level stakeholders in the energy transition in the built environment in the Netherlands?

In order to be able to answer this research question satisfyingly and to achieve the research objectives outlined in the previous section, the research objectives have been translated into the following six sub-questions.

- What is the potential role of hydrogen energy applications in the future energy supply system for the built environment in the Netherlands?
- What is the current phase of the energy transition in the built environment in the Netherlands, and what is the current position of hydrogen energy applications therein?
- What are the main opportunities and challenges for facilitation of hydrogen energy applications in the energy supply system of the built environment?
- Which stakeholders are regime level stakeholders in the governance of the energy transition in the built environment in the Netherlands?

- How are stakeholders responsible for the regime level of the energy transition in the built environment being influenced and changed by niche developments in the Netherlands?
- Which opportunities and challenges for hydrogen energy applications are present in the governance of the energy transition in the built environment in the Netherlands to foster the facilitation of hydrogen energy applications for the built environment at the regime level?

1.3 Research relevance

1.3.1 Societal relevance

This study is socially relevant because it aims to increase the knowledge on the possible position of hydrogen energy applications within the energy transition in the built environment in the Netherlands. It is currently still unclear how the many alternatives to replace natural gas could be fitted into the framework of the energy transition in the built environment and under what conditions hydrogen energy applications could have a role in this transition. This study contributes to the reduction of complexity and uncertainty in a future energy supply system of the built environment, and therefore could make it easier for stakeholders involved in energy planning and urban planning to decide on which sustainable energy alternative is suitable for a particular situation. The findings on what conditions are beneficial for facilitating hydrogen energy applications for the built environment are being translated into a set of recommendations for stakeholders involved in the Dutch energy transition in the built environment. These recommendations could enhance the institutional facilitation of hydrogen energy applications in the built environment, as well as identifying a possible strategy that leads to the formulation of policies and pathways towards a successful facilitation of hydrogen energy applications into the regime of the energy transition in the built environment.

In addition, there is not only an increased level of attention for hydrogen-based energy in the Netherlands; across Europe (European Commission, 2010) and further afield (e.g. Innovators Magazine, 2018), there also is increasing attention for hydrogen. The results of this study therefore may be of interest for international purposes and possibly contribute to investigate the potential of hydrogen energy applications for the built environment elsewhere. The NIB (2017) expressed the desire to become a frontrunner on the field of hydrogen-based energy, and an increased focus of the national government is present (SER, 2018). This research aims at investigating how such desires are being translated into tangible policies. As such, the research contributes to understanding the transfer of ambition from a national level to the regional and local levels, and vice versa. The transfer of ambition can be a source for lesson-drawing and policy transfer for other regions and possibly even countries, because strong leadership is one of the prerequisites for successful transitions (Loorbach et al., 2010).

1.3.2 Scientific relevance

For academia, studying the facilitation of hydrogen energy applications for the built environment is important in two ways. First, (following the research goals) this study aims at identifying the current position of hydrogen energy applications in a dynamic energy transition context in the built environment. Knowledge on this position is currently lacking, while it has been suggested that research in this field is beneficiary for a better-managed energy transition (Dodds et al., 2015; Rijksoverheid, 2016b; Gigler & Weeda, 2018). Second, this study examines the opportunities and challenges related to hydrogen energy applications as energy solutions for the built environment in the Netherlands. As such, this study is aimed at adding knowledge on the dimension of the built environment within the concept of the hydrogen economy, which is still very much a hypothetical concept (Balat et al., 2008; Hanley et al., 2017) within the energy transition context.

In addition, the suggested systemic changes in the current socio-technical system of the energy supply system of the built environment require a framework of understanding that is offered through transition management theory. This study focuses on the governance part of the incorporation of hydrogen energy applications in the broader concept of energy transition in the built environment, which is still very much characterised by learning-by-doing (Loorbach, 2010). Hydrogen energy applications clearly are in the niche stage, with many different innovations that are not yet clearly linked to each other. This study provides empirical knowledge on how such processes of governance in a complex governance environment happen. As such, this study investigates a phenomenon that is part of an ongoing transition in reality and can contribute to the empirical evidence to identify whether transition theory and transition management theory are applicable in practice in the case of the energy transition in the built environment in the Netherlands.

1.4 Research scope

The Dutch national government is currently discussing and designing policies on how to provide a sustainable energy supply system for the built environment, while attention for hydrogen energy applications is increasing by the day (CE Delft, 2017; SER, 2018). Many pilots involving different technologies are currently being explored or already taking place (Duurzaam Ameland, 2018; DvhN, 2018; NOS, 2018a). At all government levels, awareness of the need for systemic change in the energy supply system for the built environment is materializing (EU, 2010; SER, 2013; Rijksoverheid, 2016b). Consequently, the transition perspective is accepted in the Energy 2020 policy of the EU and the Dutch Energy Agreement (European Commission, 2010; SER, 2013; Kemp & Rotmans, 2004). The northern region of the Netherlands is, albeit hesitatingly, taking the lead in hydrogen energy applications; its history in the energy sector and a visionary document established by the Northern Innovation Board (NIB, 2017) are symptoms that political willingness is present in the region to experiment with hydrogen energy applications in the built environment. Of course, the energy transition in the built environment encompasses many other sustainable energy alternatives (see **Glossary** and **Chapter 2**) to the current energy supply system that is based on fossil energy sources. Hydrogen energy applications are just one category of sustainable energy alternatives for the built environment (based on e.g. SER, 2013; TNO, 2017; also **Chapter 2**). Although this study touches upon other sustainable energy alternatives for the built environment, it focuses on hydrogen energy applications.

Finally, discussing sustainable energy alternatives inevitably involves technical specifications. A lot of studies on hydrogen energy applications have been executed already, also for the built environment dimension of energy supply (e.g. Dunn, 2002; Dodds et al., 2015). Technical specifications and opportunities cannot be separated from their institutional and practical surroundings, however: significant barriers for the actual implementation of new technologies could be expected to be more of an institutional nature. Therefore, this research focuses on the governance activities involved with facilitating hydrogen energy applications in the built environment in the Netherlands and only briefly touches upon the technological specifications of hydrogen energy applications.

1.5 Research design

This study is divided into two different stages, which is illustrated in Figure **1.3**. The first of these two stages is focused on literature-based research and in the second stage, the insights obtained from literature research are used as starting points for an empirical, qualitative investigation of a case study.

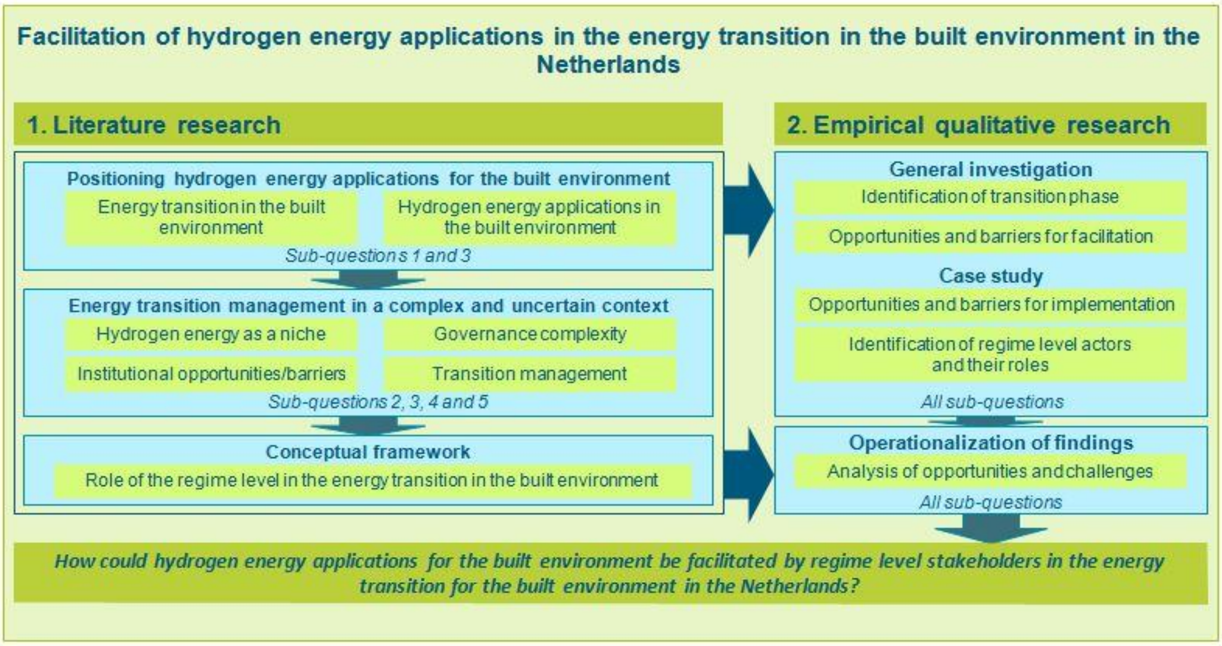


*Figure **1.3:** Research framework that is applied in this study*.

The first research phase encompasses the positioning of the phenomenon under study in the wider context (**Chapter 2**) and a theoretical framework on how such phenomena develop over time (**Chapter 3**). First, a more technical-oriented framework needs to be established to better understand the energy transition in the built environment and, consequently, how hydrogen energy applications can be fitted into the built environment (sub-question 1) and what their practical opportunities and challenges are (part of sub-question 3). Second, the social and governance related aspects (like the involvement of society and stakeholders and the governance structure of the energy transition in the Netherlands) of niche incorporation in the energy transition need to be addressed. These offer insights for systematic analysis regarding the point of departure for facilitation of hydrogen energy applications in the built environment (sub-question 2) and touch upon the governance related opportunities and challenges (sub-question 3). It also contributes to understanding how systemic change in the socio-technical regime can be induced; this helps to answer sub-question 4. Tools are provided to identify regime level stakeholders, which help to answer sub-question 5. Finally, the steps executed in the first research stages result in a conceptual framework that conceptualizes the facilitation of hydrogen energy applications for the built environment.

In the second research stage, a single case study is analysed to identify how these mechanisms work in practice. This case study is selected on the basis of a set of criteria, which will be outlined in **Chapter 4**. On the basis of qualitative data collection, the case study offers evidence how '*the seeds of a transition*' (niches) might infiltrate into the regime and what kind of stakeholders are present and influential at the regime. The case-study presents which and how governance struggles are experienced and possibly could be taken away (sub-question 6), as well deepens the understanding of the findings done in the first research phase. The case study analysis consists of a document analysis and a series of semi-structured interviews (see **Chapter 4**). The aim of the single case study is to analyse the operational processes of the mechanisms outlined above in practice, and to provide empirical evidence on opportunities and challenges. Together with the literature research and the input on more general questions on hydrogen energy, these form the basis of an analysis that consequently results in policy recommendations for policy and decision makers that are presented in **Chapter 7**.

1.6 Structure of this study

After the introduction to the background of the research topic and an overview of the research objectives as above, **Chapter 2** positions hydrogen energy applications in the wider context of the energy transition in the built environment and its associated challenges. **Chapter 3** encompasses an extensive literature study on governance and management of transitions in general and the energy transition in particular, as well as a conceptual framework in which all these elements are connected to each other. In **Chapter 4**, the methodology for this study is explained: it elaborates on how the necessary data are collected and analysed, and defends the practicability of the research strategy as well. After that, **Chapter 5** provides an introduction and background information on the case study that is investigated. In **Chapter 6**, the results of the study are being presented and discussed. In **Chapter 7** these results are then being critically discussed in relation to the literature and a conclusion on the main research question is drawn up. At last, a critical reflection on whether the goals of the study have been met and to what extent the research methods applied were suitable in retrospective, as well as it provides recommendations for further research on hydrogen energy applications in the built environment and their role in the energy transition for the Netherlands are being provided in **Chapter 8.**

2 Positioning hydrogen energy applications in a sustainable energy supply system for the built environment

This chapter aims to position hydrogen energy applications for the built environment in the wider context of the energy transition in the Netherlands, based on literature reviews. First, a short introduction on the energy supply and demand characteristics of the built environment is provided. Second, the different applications of hydrogen in the built environment are outlined. Third, the basic principles of hydrogen production, hydrogen distribution and hydrogen storage are explained. Consequently, a very short overview of other sustainable energy alternatives for the built environment is provided. Finally, the observations will be summarised and framed as being a complex issue.

2.1 Energy characteristics of the built environment

2.1.1 The built environment as an energy end-use sector

The potential position of hydrogen energy applications is dependent on the characteristics of energy supply and demand patterns in the built environment in the Netherlands. The built environment is one of the so-called end-use sectors that can be distinguished in the entirety of the energy supply system (see Table 2.1 and **Glossary**). These end-use sectors are based on their distinctive characteristics in energy demand and energy use that set them apart. The built environment accounts for roughly 20% of the overall energy consumption in the Netherlands, which is visualised in Figure 2.1. (CBS, 2018a). The built environment uses energy to fulfil in three basic energy demands: space heating supply, tap water heating supply and power supply.

*Table **2.1:** Overview of energy end-use sectors and their distinctive characteristics that set them apart from each other (after Omer, 2009; CBS, 2018a).*

Energy end-use sector	Characteristics
Energy sector	The energy sector produces energy for the other end-use sectors by converting energy sources (e.g. biomass, wind, solar power, water power, fossil energy sources) into relevant energy carriers (e.g. bio fuels, electricity, hydrogen and fossil fuels).
Industry	Industry consumes energy carriers and energy sources for the industrial production of raw materials and goods (both heat and electricity).
Transport	Transport consumes energy carriers for the movement of raw products, goods and people through space with vehicles.
Built environment	The built environment consumes energy carriers to supply heat and electricity for households, public buildings, enterprises and offices (not including the industrial production of goods and raw materials).
Other	This end-use sector includes energy consuming entities that do not fit within the other categories, e.g. water treatment, waste treatment, agriculture and fisheries.

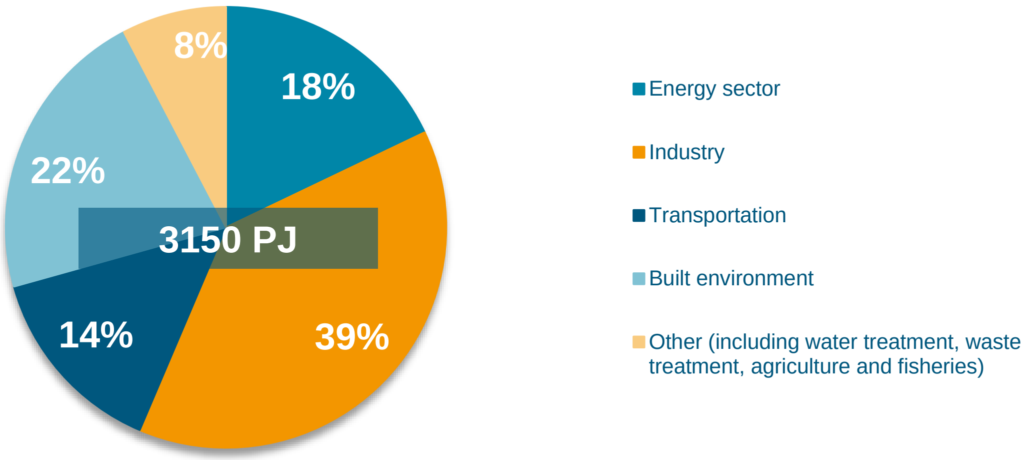


*Figure **2.1:** Overview of energy consumption by end-use sector in the Netherlands, 2017 (after CBS, 2018a).*

2.1.2 The intermittency problem and system integration

The energy consumption demands of the built environment are subject to much more daily and seasonal variety in demand when compared to other end-use sectors (Van Kann, 2015). Households, public buildings, enterprises and offices usually only heat their buildings when it is cold outside (during winter) and electronic devices like lamps, televisions and kitchen appliances are usually switched off during the night. Figure 2.2 illustrates this by visualizing the variety in energy consumption over the year 2017 in an average neighbourhood in the Netherlands. As the current energy supply system is based on controlled combustion of fossil energy sources, the energy sector is able to cope with these variations in energy demand by simply using more or less energy carriers. Most sustainable energy sources, however, are subject to both daily and seasonal supply variations as well, especially wind and solar energy. This causes an intermittency problem; it could well be the case that if energy demand is high, energy supply is low and vice versa.

The observations outlined above imply that extensive system integration is needed; such a system necessitates the ability to transfer heat into electricity and vice versa in order to increase the adaptive capacity of the network and therefore the security of energy supply (Smale et al., 2017). System integration offers opportunities to cope with this intermittency problem and is therefore especially important for the energy supply of the built environment (Clastres, 2011; Swan & Brown, 2013; De Laurentis et al., 2017; Smale et al., 2017). System integration is based on the principle of an energy mix. Virtually all renewable energy sources are not only subject to variety in supply and demand, but are also constrained by geographical conditional constraints. This forces society to switch to a mix of different energy sources in the same system and in the same time frame (Clastres, 2011). Therefore, one of the main distinctive features of the future energy supply system will probably be the creation of energy storage mechanisms. These are technologies that are able to store energy at moments when supply exceeds demand for moments when demand exceeds supply to ensure the security of energy supply (Wade et al., 2010; Darby, 2018, also see **Appendix 1)**

So far, the energy end-use sectors discussed above were related to each other in a rather static way. The energy sector converted energy sources into energy carriers for the other dimensions. By system integration, these relations are blurring as well; energy carriers can be transferred cross-dimensionally whenever needed due to network integration. This is called sector coupling (Brown et al., 2018) and it offers opportunities to execute the energy transition in a more efficient way; economies of scale enhances the financial-economic opportunities of different technologies when these are applicable on a larger scale.

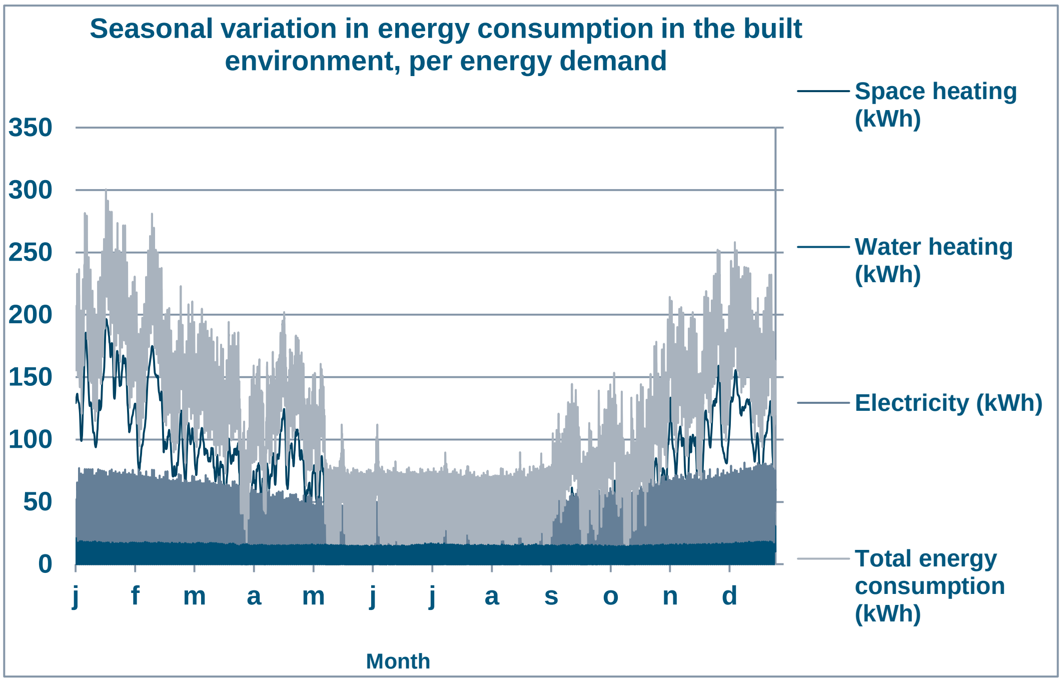


*Figure **2.2**: Yearly variation in energy consumption in the built environment, per energy demand in an average neighbourhood with 100 households in the Netherlands (after RENDO, 2018)*

2.2 Hydrogen energy applications in the built environment

The next sub-sections elaborate on the three main energy demands in which hydrogen can be applied as an energy carrier for the built environment. The section is concluded with an overview of the identified applications in which hydrogen can be used as an energy carrier for the built environment.

2.2.1 Space and tap water heating

For heat supply, hydrogen can be used both directly and indirectly (Edwards et al., 2007; Dodds et al., 2015). Direct heat supply by hydrogen works in the same way as natural gas is currently being combusted to generate heat. Hydrogen gas is transferred, eventually in a mixture with another type of gas (for example natural gas or green gas (Sierens & Rosseel, 2000; Gigler & Weeda, 2018)) to gas boilers that are suitable for the combustion of hydrogen. Direct heat supply by hydrogen is not particularly a new phenomenon, as is illustrated in **Box 1.** The heat that is generated by the combustion of gas is used to heat water that is circulated through a conventional central heating system (Dodds et al., 2015; Cellek & Pinarbasi, 2018). In the Netherlands, hydrogen gas or a gas mixture can be transported through a pipeline system similar to the current natural gas pipeline system. Natural gas pipeline systems will require some adjustments to be suitable for transporting hydrogen (Kiwa, 2016; DNV-GL, 2017). However, conventional natural gas boilers need to be replaced by new boilers that have the capability for hydrogen combustion (Dodds et al., 2015; DNV-GL, 2017). Direct heat supply by hydrogen could also be practiced on a neighbourhood level, by connecting a central hydrogen combustion boiler to a heating network (Fang et al., 2013; Dodds et al., 2015; for more on heating networks see **Appendix 1**).

Indirect heat supply by hydrogen is based on stationary fuel cell technology (Jacobson & Delucchi, 2011; Dodds et al., 2015; Cappa et al., 2015). In stationary fuel cell technology hydrogen inside the fuel cell reacts with oxygen from the air, which produces electricity, water vapour and a little heat (Edwards et al., 2008). In a system based on fuel cell technology, hydrogen is transported to a fuel cell using a pipeline or under specific conditions in suitable containers. There it is used to generate electricity that can be used for all-electric energy options, in which heat demand is fulfilled by heat pumps. More about heat pumps can be found in **Appendix 1.**

Box 1: A short history of hydrogen-based energy supply in the built environment

The possibility of hydrogen being used as an energy carrier for the built environment is not particularly a new idea. During the 19th century, scientists were already outlining the idea of hydrogen as the energy carrier of the future and thus laying the fundaments for the hydrogen economy concept. Their ideas were also romanticised by leading writers of that era, e.g. in Jules Verne's novel *The Mysterious Island* dating from 1874:

'(…) water will one day be employed as fuel, that hydrogen and oxygen of which it is constituted will be used' (Verne, 1874, p. 229).

Verne was obviously not scientifically correct, but this quote illustrates the extent to which hydrogen was seen as the future of energy in that era. Although hydrogen generation methods and technology developed over the years (with the most notable example being the gas in zeppelin airships gas cells during the early 20th century), energy efficiency loss in the generation of hydrogen and the availability of cheaper and more easily accessible energy carriers (like oil and natural gas) led to the diminishing attention on hydrogen as an energy carrier (Marbán & Valdés-Solís, 2007). The hydrogen economy concept started to regain attention after the 1973 oil crisis (Winsche et al.,1973; Gregory, 1975), and more recently, due to the increasing worldwide environmental concerns, as an alternative to fossil fuel-based energy carriers (Dunn, 2002; Barreto et al., 2003; Züttel et al, 2010) (also see Sections **1.1** and **3.1)**. Until recently, the idea of a future hydrogen-based economy was often portrayed as being economically unfeasible and technologically impractible (Cherry, 2004; Hultman, 2009). Only since the first decade of the 21st century, the concept started to gain mainstream scientific interest again after the costs of renewable energy sources like wind and solar power started to decrease significantly (Balat, 2008). Although most scholars who paid attention to the hydrogen economy concept acknowledged the energy question for the built environment, most attention has usually been given to the transportation dimension of the economy (National Research Council, 2004; Johnston et al., 2005). Hydrogen is however as well a potentially well-applicable energy carrier for the built environment, with possibilities for heat supply, electricity supply and energy storage (Dodds et al., 2015). It is now getting the attention it deserves for these characteristics once again (Edwards et al., 2007; McDowell, 2012; Hanley et al., 2017).

2.2.2 Electricity

In terms of energy efficiency, it does not make sense to make direct use of hydrogen to generate electricity on-shore for the power grid as the hydrogen first needs to produced out of other energy sources (see Section **2.3**) (Edwards et al., 2008; Ball & Wietschel, 2009; Armaroli & Balzani, 2011). However, hydrogen that has been generated to make use of excess supply of renewable electricity can be used to generate electricity in conditions of excess demand. This can be done by either conventional hydrogen combustion in power plants (like conventional natural gas power plants) or by stationary fuel cell technology like described above in Section **2.3.2** (Mathiesen & Lund, 2009; Yu et al., 2018).

2.2.3 Energy storage

Hydrogen has the physical ability to practicably store energy in situations when supply exceeds demand (Anderson & Leach, 2004). This intermittency problem is one of the key challenges in the energy transition (Wade et al., 2010; Darby, 2018) (also see Section **2.1.2**). Excess supply functions as electricity supply for water electrolysis, a process in which water is decomposed into hydrogen gas (H_2) and oxygen gas (O_2) (Gregory, 1975). In situations when demand exceeds supply, hydrogen can then be transported to conventional power plants for combustion or to (stationary) fuel cells to generate electricity like described in Sections **2.4.1** and **2.4.2** (Edwards et al, 2008).

In an integrated energy system, where the relationships between energy producers and consumers are blurring, like described in Section **2.1.2**, this hydrogen opportunity also provides the opportunity to store excess locally produced solar or wind energy on a neighbourhood level in the condition of hydrogen gas by small-scale electrolysis. This provides opportunities for neighbourhoods in isolated areas or willingly off-grid developments to still be able to secure energy supply. Storage of hydrogen gas in this situation could take place in small gas containers or even in hydrogen fuel cell-based vehicles, which is a good example of cross-dimensional use of energy carriers (Guille & Cross, 2009). For more on the principles of energy storage by such power-to-gas technologies, see **Appendix 1**.

2.2.4 Overview of hydrogen energy applications for the built environment

Summarizing, in the energy supply system for the built environment, hydrogen could fulfil a role in the following ways:

*Table **2.2:** Overview of hydrogen energy applications for the built environment, distinguished by scale level.*

Energy demand	Space and tap water heating	Electricity	Energy storage
Household level	**1. Conventional combustion in gas boilers 2. Stationary fuel cell technology**	**Stationary fuel cell technology**	**Household level fuel cell/electrolysis combination (e.g Battolyser)**
Neighbourhood level	**1. Conventional combustion to fuel heating network 2. Stationary fuel cell technology to fuel heating network**	-	**Neighbourhood electrolysis plant**
Energy supply system level	-	**Combustion of hydrogen to fuel conventional gas power plant**	**Storage and admixing of hydrogen in gas grid from power plants**

2.3 Production, distribution and storage of hydrogen

2.3.1 Hydrogen production

One of the most significant limitations to hydrogen as an energy carrier is the fact that it always has to be generated out of other energy carriers; every hydrogen production method that has been developed so far, resulted in a loss of energy efficiency (Holladay et al., 2009; Armaroli & Balzani, 2011). The (physical) law of conservation of energy namely involves an equal net energy result after every conversion (Giancoli, 2008). Consequently, the production of hydrogen as an energy carrier is only economically feasible in situations that the costs of energy carrier supply are higher than the costs of energy carrier demand.

Another issue related to hydrogen production is the sustainability (and maturity) of the different production methods. According to Holladay et al. (2009), there are two general methods for hydrogen production based on the sources they use: carbohydrate-based (both fossil and renewable) and water-based methods. The European project of CertifHy introduced a colour system to distinguish three different types of hydrogen based on the sustainability of the production processes, which is summarised in Table 2.3. An overview of all technologies that could be applied to produce hydrogen and their sustainability degrees is to be found in **Appendix 2.1.**
Hydrogen production from fossil fuels is not sustainable on the long term; besides the fact that it involves a net loss of energy efficiency, it is also accompanied with CO_2-emissions. The European ener-

gy sector identifies hydrogen that is produced with this method as *grey hydrogen* (CertifHy, 2018). There might be good reasons to produce hydrogen for energy carrier purposes using fossil fuel-based methods, however. At first, hydrogen as an energy carrier does not involve local CO_2 emissions or other pollution effects, regardless of the way it has been produced (Armaroli & Balzani, 2011; Hanley et al., 2017). The sustainability of grey hydrogen can be improved by taking CCS/CCU measures (Dincer & Acar, 2015; Koytsoumpa et al., 2017; also see **Glossary**). Although CCU measures which are economically profitable are still very limited, significant progress is taking place in this field (Koytsoumpa et al. 2017). By taking these measures, the hydrogen that is produced is called *blue hydrogen* by the European energy sector (CertifHy, 2018). This type of hydrogen is proposed by the Leeds City Gate Project management, for example, in order to accelerate the technological developments related to hydrogen equipment in an economically feasible situation (for further info, see Leeds City Gate Project (2017)).

For sustainable energy supply with hydrogen energy applications, hydrogen production is preferably done by water electrolysis with sustainably generated electricity from renewable sources (Turner, 2004; Balat, 2008). This type of hydrogen is called *green hydrogen* by the European energy sector (CertifHy, 2018). There are three main factors that inhibit large scale hydrogen production by sustainable electricity-driven water electrolysis, however: 1) electrolysis efficiency (see **Appendix 2.1.),** 2) electrolysis plant capacity and 3) sustainable electricity availability (CertifHy, 2018; Gigler & Weeda, 2018). Although electrolysis is a process that has been known for decades already, its efficiency has been the most inhibiting factor for wide use; it requires a lot of electricity for a rather small amount of hydrogen gas (Holladay et al., 2009; Dincer & Acar, 2015). The capacity of electrolysis plants is an issue as well. Currently, the biggest power-to-hydrogen gas plant (a PEM-electrolyser) has a capacity of 10MW, while the average is at just around 1MW (FCH Europa, 2018). The technological developments in this field are quite significant, however, and will likely develop faster whenever demand increases (Ball & Weeda, 2015). The most inhibiting factor, however, currently is the limited availability of sustainably generated electricity (Dincer & Acar, 2015).

*Table **2.3**: The three distinguished types of hydrogen and their production methods in relation to CO_2 production.*

Hydrogen type	Production method
'grey' hydrogen	Fossil fuel reforming, without CCS/CCU-measures
'blue' hydrogen	Fossil fuel reforming, with CCS/CCU-measures
'green' hydrogen	Electrolysis with sustainably generated electricity (no carbon production); Carbohydrate-based methods using biomass (renewable carbon production)

2.3.2 Hydrogen distribution and storage

Hydrogen can be transported like natural gas through pipelines (Dodds et al, 2015; Fekete et al., 2015; Gigler & Weeda, 2018). As the Netherlands is planning to eliminate natural gas as an energy carrier, the pipelines that have been used for natural gas distribution offer an interesting medium for hydrogen gas distribution (DNV-GL, 2017). Some adjustments will have to be made to the existing natural gas network, however, which will of course require investments. The main reason is that it is likely that hydrogen molecules will escape through cracks in conventional natural gas pipelines; hydrogen molecules are much smaller than natural gas molecules. Another issue related to hydrogen pipelines is that the small molecules involve a low density as well, which means that more pressure is needed to transport the same amount of hydrogen molecules (Fekete et al., 2015; DNV-GL, 2017). For transportation in the built environment, using the existing natural gas pipeline network is beneficial in two ways; it reduces the depreciation of existing energy infrastructure (DNV-GL, 2017) while reducing the need to invest in alternative networks as well. The electricity network in particular will be under increasing pressure in the case a shift from gas to electricity solutions will be made (Verfondern & Teodorczyk, 2007; Dodds et al., 2015). Distribution of hydrogen in containers or vehicles is an alternative for areas that are not connected to the gas pipeline network or for extra storage capacity, like described in **Chapter 5** (Anderson & Leach, 2004; Edwards et al., 2008; Guille & Cross, 2009).

There are four different methods for hydrogen storage. All storage mechanisms have different transportation methods connected to them (Niaz et al., 2015). Niaz et al. (2015) discuss these methods and their respective advantages and disadvantages, of which an overview can be found in **Appendix 2.2.**

2.4 Other sustainable energy alternatives

Although the various applications of hydrogen for heat generation, electricity generation and energy storage discussed in Section **2.2** are technically suitable for a sustainable energy supply system for the built environment, there are many other technically feasible sustainable energy alternatives as well. This section provides a very short overview of the other options that are 1) sustainable (see **Glossary** for a definition) and 2) practically applicable in relation to the built environment and 3) market ready (Rogers, 2010; Walsh, 2012). It goes beyond the scope of this study to elaborate on the technological background of all the different options in detail. The five main alternatives to hydrogen energy applications that are currently considered in the Netherlands are shortly addressed here. A limited explanation on the operational processes of the discussed technologies can be found in **Appendix 1**.

Heating networks: Heating networks (or district heating) are networks of pipeline through which hot water, fed by residual heat from industries and power plants, is distributed to practically reuse the exergetic value of endothermic processes (Van Kann, 2015, see Glossary). District heating is only useful for areas that are located in the relative vicinity of such heat-generating plants, although it is a robust way to make efficient use of residual heat that would otherwise be lost (Raven & Verbong, 2007; Fang et al., 2013; Connolly et al., 2014).

Solar boilers: Solar boilers are appliances that collect thermal solar energy to heat water. They can be used to fulfil heat demand. The heat-collecting appliance of a solar boiler is installed on the roof of a building in the same way as a solar PV-panel. In the climate conditions of the Netherlands, this is necessary to have hot tap water and space heating during winter as solar heat alone will not be sufficient during the colder winter months (MilieuCentraal, 2018).

Heat pumps (*all-electric*): Heat pumps are appliances that transfer thermal energy in the opposite direction compared to the natural situation. In the Netherlands, this option is often called the *all-electric* option (Rijksoverheid, 2016b; SER, 2018). Heat pumps are only suitable to fulfil heat demand. There are many different types of heat pumps, but all types share this same principle (Scoccia et al., 2018). Houses need to be insulated very well before heat pumps are feasible. (Omer, 2008).

Geothermal heat: Geothermal heat makes use of the thermal energy from the earth's core (Barbier, 2002; Lund et al., 2011). By pumping hot water into deep into the earth's crust and then up into a heat exchanger, water is heated that is circulated through a pipeline system in the built environment. (Dickson & Fanelli, 2013).

Electricity storage systems: Electricity storage solutions comprise technologies that are able to store excess electricity supply for periods when demand exceeds supply by converting electricity into chemical and kinetic energy (Hadjipaschalis et al., 2009; Yu et al., 2018). The most common technologies are flywheel technology, battery electricity storage systems, compressed air storage and pumped water storage (Hadjipaschalis et al., 2009; De Boer et al., 2014). The ‘preferred’ (the most suitable) electricity storage solution depends on the situational circumstances (Mathiesen & Lund, 2009; Luo et al., 2015).

2.5 Bringing hydrogen energy applications for the built environment into the energy supply system: a complex issue

The previous sections discussed several observations on hydrogen applications for the built environment and their opportunities and challenges for the energy transition in the built environment. First, it is argued in Section **2.1** that the built environment is subject to a large variety in daily and seasonal variety in energy demand and therefore requires an energy supply system that is able to cope with large fluctuations in both energy demand and energy supply. Second, Section **2.2** elaborated on how hydrogen could be used in the built environment in different hydrogen energy applications. Third, Section **2.3** elaborated on how hydrogen can be produced, distributed and stored. Last, in Section **2.4** it has been outlined that these hydrogen energy applications have many sustainable alternatives.

These observations illustrate that the facilitation of hydrogen energy applications by stakeholders to incorporate them into the energy transition is a rather complex issue. Due to these characteristics of both the built environment as an energy-consuming entity and hydrogen energy applications, stakeholders connected to the energy transition in the built environment struggle to identify which sustainable energy supply method is most suitable for their specific situation. Policy makers have difficulties with creating policies that aim to upscale sustainable energy innovations, as there are many different alternatives that require conditions that could be contradicting. It fits within the wider development that the energy supply system for the built environment, its stakeholders and its objects are subject to an increase of mutual interdependencies and interrelationships amongst each other and in relation to their context. **Chapter 3** elaborates on how such complex issues could be studied in terms of governance.

3 Theoretical framework: transition management in a complex and dynamic governance context

The theoretical framework provides a perspective on the governance of sustainable innovative niche development in a dynamic and complex governance context, by elaborating on theories and concepts that could help to understand the governance of facilitation of hydrogen energy applications in the built environment. First, hydrogen energy applications are framed as a sustainable innovative niche. Second, it is outlined why it makes sense to study the facilitation of hydrogen energy applications in a transition context. Third, governance-related challenges involved with the energy transition in the built environment will be addressed, including complexity, uncertainty and the impact these have on the willingness and ability of stakeholders to act. Fourth, a multilevel governance perspective then illustrates how the division of responsibilities between different stakeholders might be crucial to overcome the challenges. The fifth section emphasises on how transition management provides a tool for analysis the governance of facilitating hydrogen energy applications in the energy transition in the built environment and Dutch energy planning. Special attention is given to the development from niche to regime, as the regime level is considered the most important level within a transition (see Sections **3.2, 3.4** and **3.5).** Last, a conceptual framework (in which all these theories and concepts are related to each other and could function as a tool for further analysis) will be provided.

3.1 Hydrogen energy applications for the built environment as a sustainable innovative niche

In order to establish a sustainable energy supply system for the future, it is necessary that irreversible changes take place in the socio-technical system of energy supply for the built environment (see Section **1.1**). These changes are meant to facilitate sustainable energy alternatives, which are induced by sustainable innovative niches (after Geels, 2004; Noseleit, 2017).

3.1.1 The development of sustainable innovative niches

Sustainable innovative niches are innovations that aim at reducing the impact of technologies on the environment compared to the technologies they offer an alternative for (Pearson & Kemp, 2007; Van den Bergh et al., 2011; Noseleit, 2017). Such innovations are often described as radical innovations, as they tend to be based on entirely different technologies than more conventional solutions (Walsh, 2012). These innovative developments are associated with new combinations that offer societal and economic opportunities additional to the environmental benefits (Alkemade et al., 2011; Walsh, 2012). Hydrogen energy applications for the built environment can be classified as an example of such sustainable innovations (Agnolucci & McDowall, 2007; McDowall, 2012), as they are innovations that aim at reducing the impact on the environment that is caused by the existing, conventional products and systems and they can be radically different from these (Van den Bergh et al, 2011; Walsh, 2012).

Sustainable innovations are ultimately a result of dynamic interaction and co-evolution between different stakeholders, in which the relationships between markets, organisations, politics and society are changing (Rotmans et al., 2000; McDermott et al., 2002; Geels, 2004). Such innovative developments that emerge bottom-up in society seem to fit very well with the niche level of the multilevel perspective on transitions (which will be further elaborated on in the Sections **(3.2** and **3.4)**); these are the niches in the transition, and it is at this level where radical innovations take place (Schot & Geels, 2008). Strategic niche management is an approach that offers a tool to analyse the upscaling of such sustainable innovative niches. If they are successful, sustainable innovative niches like hydrogen energy applications for the built environment could scale up, gain a larger market share and foster progress of the existing energy supply system for the built environment (Kemp et al., 1998; Schot & Geels, 2008; Caniëls & Romijn, 2008; Ruggiero et al., 2018). To understand how sustainable innovative niches can successfully scale up, the theory of diffusion of innovation by Rogers (2010) provides a helpful tool.

Although diffusion of innovations as theorised by Rogers (2010) is an approach to analyse the market infiltration of innovation in products (and thus not so much of systems, like the energy supply system under study), it offers a theoretical perspective on how innovations develop over time. Several authors (e.g. Walsh, 2012; Ruggiero et al., 2018) adopted a similar perspective on the upscaling and development of sustainable innovations of renewable energy technologies. Although there is a wide variety of hydrogen energy applications for the built environment that could be applied (see Section **2.2.4**), these are based on rather similar technologies (Dodds et al., 2015; Gigler & Weeda, 2018) and therefore the diffusion of innovations approach is being applied. System innovation, as described by Elzen et al. (2004), does not emphasize as much on the separate technologies within systems and is more applicable on the wider energy supply system that is undergoing a transition (see Sections **3.2-3.5**).

By determining the phase of diffusion in which the hydrogen energy applications for the built environment are, it will be easier to determine how these innovative hydrogen energy applications could eventually infiltrate the regime of the energy transition in the built environment.

Geels & Schot (2007) provide four key prerequisites for niche innovations that indicate if these niche innovations are suitable to upscale into the regime:

- Innovations have been materialised into a dominant product design after processes of learning and experimenting
- Innovations have been supported by a number of influential stakeholders within the regime;
- Innovations have a feasible price-quality ratio;
- Innovations have gained 5% or more of the market share within their market.

In turn, Walsh (2012) argues that the degree of upscaling of innovations from the niche to the regime depends on two factors. First, the degree of upscaling depends on the extent to which innovations are stimulated in the market through the creation of supply. Second, the degree of upscaling depends on the extent to which there is a demand for the sustainable innovative niches in society. Demand for innovations and supply of innovations will increase when an innovation can deliver its added value in a market in order to convince the market that the innovation is believed to have enough necessity and urgency (Walsh, 2012).

3.1.2 Diffusion of innovations

A useful tool to analyse the development of an innovation can be found in the communication and evaluation of applications of innovations. This communication and evaluation of products takes place in phases, which refer to the different scale levels to which a new technology is applied (Rogers, 2010). In Figure 3.1, the different phases are presented in a schematic overview. Below the figure, phases 1 till 3 will be elaborated on. **Box 2** elaborates on the other two phases.

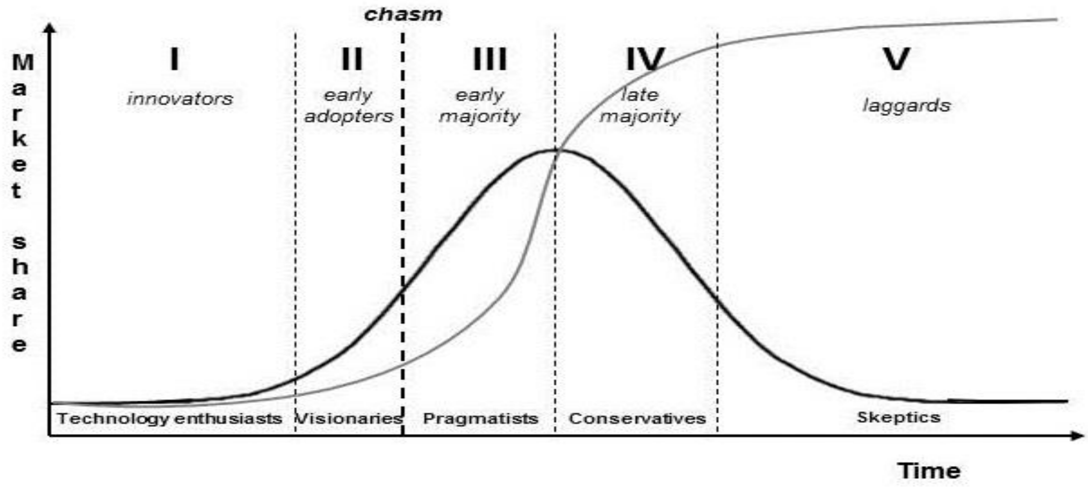


*Figure **3.1:** Model of diffusion of innovations (after Rogers, 2010).*

- Phase 1: *innovators*

During the first phase, a new technology has not yet been able to be applied on a large scale. At this stage, pioneering developers and front runners are getting interested in new innovations. These are often people who have followed high education and who are prepared to take a risk by introducing a new product (Rogers, 2010). In this phase there may still be many doubts about the new product (Wei & Chin in Dagdougui, 2012) and it may be that these new products do not yet fit well into the existing socio-technical system. In this phase of development, new products are often still underdeveloped, have not yet been extensively tested and many adjustments are still needed (Kemp et al., 2007). In addition, the preferences of consumers with regard to the new product are often still underdeveloped (Kemp et al., 2007).

- Phase 2: *early followers*

During the second phase, the innovations are picked up by a number of early followers (Rogers, 2010) These are often stakeholders who already had some kind of confidence in the innovation, but for whom the risks were too uncertain or too high to be a frontrunner. The scale on which a technology is applied becomes larger and confidence in the technology is growing (Rao & Kishore, 2010).

- Phase 3: *early majority*

During the third phase, the processes described under the previous phase continue, until the level that an early majority uses the new innovation (Rogers, 2010). The larger the scale on which a new innovation has been applied and the more experience has been gained with the new product (Rao & Kishore, 2010) and the more a product has practically proven itself to the consumer (Kemp et al., 2007), the higher the chance that an innovation reaches this stadium. Ultimately, the larger the scale on which a new product is applied, the cheaper the new product will be because of an increased yield (Zafarzynska & Van den Bergh, 2010).

Box 2: the last two phases of the diffusion of innovations model by Rogers

- Phase 4: *late majority*

During the fourth phase, the new innovation might result in a mature market, which might mean in terms of transition theory that a new dynamic equilibrium is achieved (Geels & Rotmans, 2001). In this stage, it is attractive for stakeholders to adopt the innovation as well, in order not to lag behind to less profitable or beneficial techniques. A late majority arises, in which most stakeholders are using the technique.

- Phase 5: *laggards*

In the fifth phase, laggards are the last stakeholders to adopt the innovation. Stakeholders who can be considered laggards usually have an aversion to change-agents and tend to be focused on traditions, while not seeing the necessity and urgency to innovate.

It seems to be rather clear that technologies for hydrogen energy applications for the built environment in the Netherlands are currently in the first phase of diffusion. Hydrogen energy applications have already become market-ready (also see Section **2.2**), although they have not yet been able to achieve a large scale of actual application. The first commercial experiments and pilots are currently being executed. One of the reasons for that is that until the second phase of diffusion, innovations often suffer from relatively high investment costs compared to existing systems. Existing systems have already benefited from economies of scale, costs, performance, knowledge and routines (Elzen et al., 2004; Hekkert et al., 2007). Innovations have not yet been able to obtain any returns with the achievement of economies of scale (Safarzynska & Van den Bergh, 2010). This is also particularly true for hydrogen energy applications for the built environment. Due to these high initial costs of development, hydrogen energy applications for the built environment are currently not yet competitive with existing alternatives (Dodds et al., 2015).

3.2 Hydrogen energy applications as a niche in the energy transition in the built environment

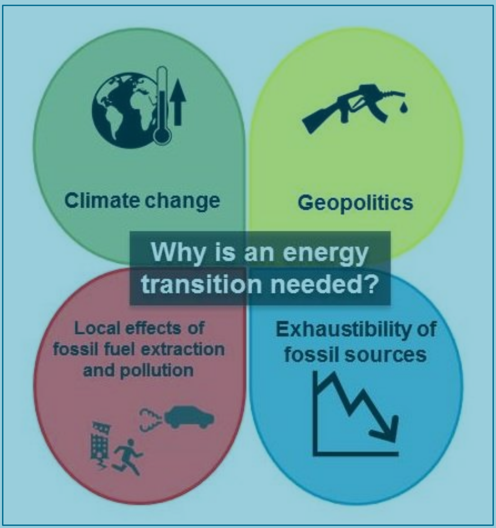
3.2.1 Framing the incorporation of hydrogen energy applications as a transition

Chapters 1 and **2** already touched upon the fact that hydrogen energy applications for the built environment are sustainable innovations in an energy supply system under transition, which has also been confirmed in the last Section **(3.1).** Like what has been argued there as well, sustainable innovations like hydrogen applications for the built environment could also be considered innovative niche developments from a transition theory perspective; niches are new developments in the socio-technical system that are expected to face several practical and institutional challenges (Rotmans et al., 2001; Geels, 2011; Loorbach, 2010). The main reasons for that are the radical and irreversible changes in the energy supply system, both physically and institutionally, that are required for facilitating hydrogen energy applications in the built environment. Such changes necessitate a transition to occur. As argued in **Chapter 1**, ongoing processes like an increasing societal demand to shift away from fossil fuels and cheaper renewable energy production indicate that this transition is already ongoing: niche developments are trying to infiltrate into the current energy supply system regime of the built environment, which is noticed by influential stakeholders. For analysing such irreversible systemic changes, transition theory functions as a useful tool (Geels, 2011). Three key concepts for analysing a transition are distinguished: the basic principles of 1) different phases of a transition, 2) the multi-level perspective (to be addressed in Section **3.5)** and 3) transition management (after Van der Brugge et al., 2005; Loorbach, 2010 (also see Section **3.6)**.

Transitions are '*transformation processes in which society changes in a fundamental way over a generation or more'* (Rotmans et al., 2001, p. 15). Transitions imply '*a shift from an initial dynamic equilibrium to a new dynamic equilibrium*' (Kemp & Rotmans, 2004, p. 140) and apply to societal complex systems, like the energy supply system for the built environment (also see Sections **2.5** and **3.1**). The transition addressed in this study is the transition from the current (fossil-based, top-down) energy supply system for the built environment to a sustainable multi-source and multi-solution based energy supply system for the built environment. Due to the necessary fundamental changes in society, it takes at least 20 to 25 years before a new equilibrium with a new energy supply system could be reached (Rotmans et al., 2001). This depends, amongst other issues, on the current phase of the transition (Rotmans et al., 2001). Inducing, analysing or even steering a transition is not a straightforward activity or process, due to the non-linear developments that are an essential characteristic to a transition (Rotmans et al., 2001; De Roo, 2010). This makes it hardly possible to draw a step-by-step approach for stakeholders at the regime level to follow (Kemp & Rotmans, 2004). For a deeper background of the need for an energy transition, see **Box 3**.

Box 3: Understanding the need for an energy transition

It is important to keep in mind why society actually needs to induce the transition towards a sustainable energy supply system for the built environment. Since the 1970s, there has been an increasing awareness within society that the current energy supply system energy is not sustainable on the long term. Especially the publication of the report by the World Commission on Environment and Development (better known as the Brundtland Report) in 1987 and the reports published by the Intergovernmental Panel on Climate Change since 1990 (WCED, 1987; IPCC, 2007; IPCC, 2014) caused a significant mobilisation of stakeholders to address these problems in policy (Nordlund & Garvill, 2002; Wheeler, 2008). The reasons behind this awareness can be distinguished into 4 categories: Firstly, fossil energy carriers are exhaustible and will likely increase in price when supplies decrease. This effect is only becoming increasingly likely to happen due to increasing population pressure and, as such, increasing demand for energy (WCED, 1987; Armaroli & Balzani, 2006). Secondly, energy supply with fossil energy carriers involves the emission of CO_2 and other greenhouse gases in a (geologically very short) time frame that have been stored in the earth during many millions of years (Hughes, 2005; IPCC 2007). There is broad scientific consensus that this leads to severe climate change that threatens a large share of the human population on the long term (Smit & Wandel, 2006). This is also especially true for the Netherlands, which is a country that is especially vulnerable to the sea level rise that is a consequence of climate change (Katsman et al., 2011). The third reason has a more (geo)political nature: fossil fuels reserves are strongly spatially concentrated. Many fossil fuel reserves are located in countries with a controversial political situation (such as Russia and countries in the Middle East) where many stakeholders do not want to be dependent on. For them, self-sufficiency and independency are key concepts of a future energy supply system (Gnansounou, 2008). At last, the extraction and use of fossil fuels can have severely negative local side effects, such as earthquakes induced by natural gas extraction in the Dutch province of Groningen (Van der Voort & Vanclay, 2015; NAM, 2018) and air pollution (Kampa & Castanas, 2008). To avoid these risks as well as to reduce the impact of these risks while still being able to secure energy supply for future generations, a well-organised transition towards an energy supply system based on more sustainable energy carriers is needed, and these interests have to be internalised and integrated in the process of policy making (Lemos & Agrawal, 2006; Jordan, 2008; Haasnoot et al., 2013).



Source: own work

3.2.2 Phases of a transition

Despite the optimism and attention for a possible future (partly) hydrogen-based energy supply system for the built environment, there has been a lack of science-based analysis regarding the point of departure for a possible transition towards an energy supply system of the built environment in which hydrogen energy applications fulfil a role. Determining the point of departure is crucial to reduce frustrations and obstacles in the planning process, as the roles of stakeholders differ per phase of a transition (Loorbach, 2010). Consequently, if the current phase of the transition can be recognised, the corresponding roles of the government levels can be determined. Therefore, it is essential to elaborate on the characteristics of the phases of a transition. Loorbach (2007) argues that a transition consists of four phases: the pre-development, take-off, breakthrough and the final stabilisation phase. The phases are distinguished by the size and speed of the fundamental changes that are taking place, as illustrated in Figure 3.2 (Loorbach, 2007). For this study, the first and second phases are of particular interest because it is clear that hydrogen energy applications in the built environment are not yet widely adopted or implemented in the current system: a break-through has not yet taken place. The final two phases are characterised by structural changes and a broad acceptance by society (via learning processes) of hydrogen energy applications in the built environment, which is currently absent (McDowall, 2012). Therefore, only the first two phases are elaborated on in the text. **Box 4** shortly addresses the other two phases.

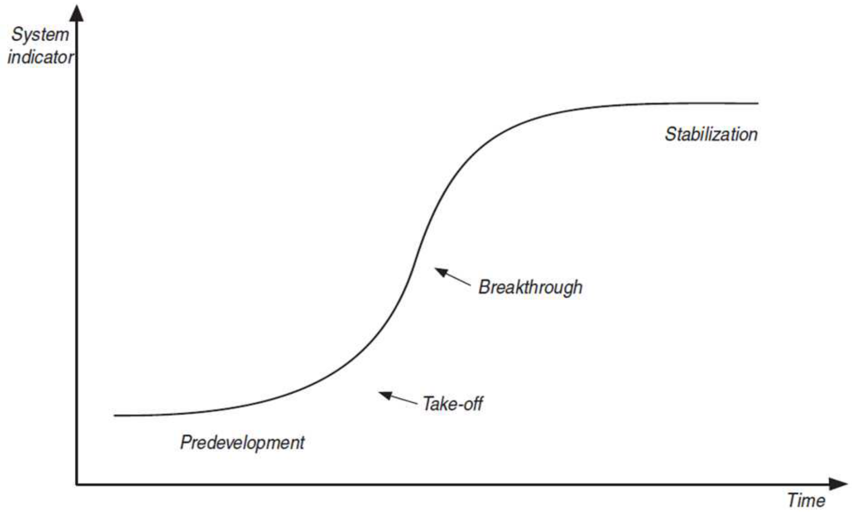


*Figure **3.2**: Transition S-curve with the four distinguished transition phases, after Loorbach (2007).*

- During the pre-development phase niches occur without visible changes in the status quo. Single buildings in isolated contexts are put to the test with new technologies (e.g. a small electrolyser that generates hydrogen gas that is used for a fuel cell in a scooter that can deliver hydrogen to the Green Village in Delft (The Green Village, 2018)**.** In this phase, governments should catalyse and facilitate these innovations (Rotmans et al., 2001). Stakeholders can stimulate niches (Caniëls & Romijn, 2008; Geels, 2011), e.g. governments subsidizing R&D for electrolysis technology efficiency (e.g. Rijksoverheid, 2018c).
- During the take-off phase the process of change is starting and the current energy supply system is slightly shifting (e.g. the first residential development project that uses hydrogen energy is being developed). In this phase, an accumulation of developments has to be created by governments and frontrunners (stakeholders) have to be mobilised, e.g. the Northern Innovation Board and its proposal for the Green Hydrogen Economy (NIB, 2017). Without a network of frontrunners, innovations will perhaps not be noticed by rigid regime stakeholders, and will not get an opportunity to become widely accepted or implemented.

Box 4: the last two phases of the transition multiphase approach by Loorbach

- During the break-through, the process of change is reaching a point of no return, whereby the regime shifts in favour of the new development. In this phase, the new technology acquires a dominant position and rigid regime stakeholders become willing to adopt a niche development (Loorbach, 2007))
- During the stabilisation phase, a new equilibrium has been reached (Geels & Rotmans, 2001). In this phase, the new system has replaced the old system and the cycle can start again if new niche developments arise (Loorbach, 2007).

Reflecting, the first two phases can be distinguished by the differences in the speed of systemic change. For the take-off phase to be reached, society has to accept hydrogen as an energy carrier to some extent, because otherwise the system would not start to shift (Rotmans et al. 2001). The degree of social acceptance and involvement may help to determine the current transition phase. For a further elaboration on how niche developments could penetrate the regime level, also see Sections **3.4** to **3.6.**

The phase approach that Loorbach (2007) uses to analyse transitions, resonates remarkably well with the diffusion of innovations model by Rogers (2010); the market share curve seems to match perfectly with the transition S-curve. The first diffusion of innovations phase, in which the innovation does not yet match existing socio-technical systems (Kemp, 2007) is roughly the same as the pre-development phase in transition theory, while the take-off phase fits well to the phase of the early adopters, in which stakeholders that have trust in an innovation are willing to adopt a new innovation (Rao & Kishore, 2010). A break-through (transition theory) than takes place when there is an early majority (diffusion of innovations; Rao & Kishore, 2010). The fourth and fifth phases of diffusion of innovations are not distinguished by Loorbach (2007); he defines these two phases as the single phase of stabilisation in a transition. In the remaining part of this study, the names of the phases distinguished by Loorbach (2007) will be consistently used to refer to both theories, unless diffusion of innovations is explicitly referred to.

3.3 Institutional challenges for facilitation of hydrogen energy applications for the built environment in the Netherlands

In **Chapter 2,** a number of opportunities and challenges related to the energy transition in the built environment, hydrogen energy applications and other sustainable energy alternatives for the built environment were addressed. In Section **1.1** it has been argued that the implementation of hydrogen energy applications in the built environment is expected to face governance-related, institutional challenges as well, which are probably even more important (Campbell, 2006; Meadowcroft, 2009; Loorbach, 2010). The built environment has an extraordinary wide range of stakeholders (Campbell, 2006; Meadowcroft, 2009; Loorbach, 2010). These stakeholders have conflicting interests and a wide array of institutions is applicable to them. This causes a lot of dilemmas (Lemos & Agrawal, 2006). This section addresses a set of different categories of challenges to facilitation of hydrogen energy applications in the built environment in the Netherlands, as well as a more theoretical background of these challenges.

3.3.1 Complexity of the energy transition in the built environment

The context in which the energy transition in the built environment occurs, is complex because of the fact that both the number and the interdependency of relationships between energy sources, energy carriers, energy supply, energy demand and energy planners are increasing, due to a more dynamic, spatially dispersed and intermittent energy supply system, and that has consequences for the governance of the energy supply system (Stoker, 1998; De Boer & Zuidema, 2013; De Roo, 2017). Complexity requires a different approach for planning, (De Roo, 2010). For the energy transition in the built environment, this means that the efforts to develop a new energy supply system are determined by the willingness as a result of a sense of urgency on the one hand and the ability as a result of a sense of control on the other (Jordan, 2008; Meadowcroft, 2009). See **Chapter 2** for a more in-depth analysis on why the facilitation of hydrogen energy applications for the built environment is such a complex issue

3.3.2 Uncertainty

Although there is wide consensus about the senses of urgency and control for a sustainable energy supply system for the built environment nowadays, it is still quite uncertain how the energy transition in the built environment will exactly materialise in each situation (after Campbell, 2006).This illustrates that the energy transition in the built environment is not only taking place in a complex context, but this context is also deeply uncertain (Campbell, 2006; Meadowcroft, 2009). Like what is argued in Sections **2.2-2.4**, there are many possible measures that could be taken that each have their own opportunities and challenges. With such a wide range of different options for heat supply, electricity supply and energy storage for the built environment in different stages of development, it is hard to distinguish which of these options will be suitable for a particular situation on the long term (Meadowcroft, 2009; De Roo, 2010). Therefore policy makers should *'create a strategic vision of the future, commit to short-term actions, and establish a framework to guide future actions'* (Haasnoot et al., 2013).

3.3.3 Path dependency of institutions

Complexity and uncertainty regarding the energy supply system have impact on the ideas, thoughts and views stakeholders have on the energy transition in the built environment and on hydrogen energy applications therein. The current energy supply system for the built environment and its associated infrastructures are a result of continuous improvements to systems that were designed in the course of the past (De Boer & Zuidema, 2013). The construction of power plants and the natural gas and electricity grids, for example, involved enormous investments that have long payback periods. Therefore, changing such systems creates governance problems and involves challenges, as security of supply, safety and efficiency should remain ensured (Duit & Galaz, 2008; Winzer, 2012), while other needs have to be incorporated in a system not initially designed to cope with such needs (De Boer & Zuidema, 2013). Such path dependencies could result in lock ins, like Nykvist & Whitmarsh (2008) discovered to be true for mobility systems. That involves high investment costs to adapt such as system to changing ideas, and drastic spatial and institutional changes will be necessary (Kemp, 1994).

This is reflected in the way institutional design is executed in such a context: the issues of complexity and uncertainty combined with the great importance and high investments required for systemic change in the energy supply system results in reluctance among stakeholders to invest in sustainable energy alternatives (De Roo, 2010; Rogers, 2010). Radical changes in the energy supply system require significant investments with often long payback periods, while their financial sources require certainty that investments are profitable before they invest. This is particularly true for households and SMEs, which comprise the great majority of the users of the built environment (Walsh, 2012; Van Doren et al., 2018).

3.3.4 Involvement of stakeholders and society

The entirety of ideas, thoughts and views of stakeholders constitute informal the institutions on energy supply for the built environment (Alexander, 2005; Duit & Galaz, 2008; Olsen, 2009). Informal institutions are socially fragmented among (groups of) stakeholders and can be determined by a wide range of factors, which results in a prioritisation of different interests. When translated to the energy supply for the built environment, the different prioritisations and visions on e.g. sustainability, efficiency, safety, security of supply and investments costs constitute informal institutions (Nilsson et al., 2011). These represent the degree of willingness to facilitate hydrogen as an energy carrier for the built environment; a sense of urgency is required (Jordan, 2008; Loorbach, 2010). On the long term, institutions are subject to change. However, this only happens if there is broad consensus among stakeholders about the need for institutional change, which is difficult to steer and often takes a lot of time (Kim, 2011). Kemp & Rotmans (2004) argue that in order to create acceptance, trust and understanding for niche developments, the involvement of society and conducting a learning-by-doing approach are crucial. A shared perspective among a wide range of different stakeholders is argued to be needed for niche developments to be upscaled (Wüstenhagen et al, 2007). In modern democracies, the different informal institutions that are shared by groups of stakeholders come together in the political arena (Olsen, 2009; Azari & Smith, 2012). There, the different ideas and prioritisations form the informal institutional framework for policy-makers (Nilsson, 2011). The three commonly shared interests on the energy supply system for the built environment are security of supply, economic efficiency and environmental sustainability (Kern & Smith, 2008; Winzer, 2012). The balance between these interests determines the willingness of stakeholders to facilitate and/or implement sustainable (Nilsson et al., 2011).

3.3.5 Formal institutions as an inhibiting factor for innovation

The formal institutional framework on energy supply then reflects these shared desires of society and thereby constitutes the acting space of stakeholders (Olsen, 2009). The formal institutional framework determines the space in which stakeholders have the ability to facilitate hydrogen energy applications for the built environment, as the formal institutional framework is the translation of the informal institutional by the political arena into (binding) laws, regulations and guidelines concerning the energy supply system for the built environment (North, 1991; Grzymala-Busse, 2010). This formal institutional framework currently aims at facilitating a secure, economically efficient and sustainable energy supply system (Kern & Smith, 2008, Winzer, 2012). Just like informal institutions, formal institutions are subject to change over time. But as formal institutions are the result of a societal debate among different stakeholders, where broad consensus among stakeholders is needed, this takes even longer (Mahoney & Thelen, 2010; Kim, 2011). Due to the mandatory, binding nature of the formal institutional framework, experimenting with hydrogen energy applications can only be performed within the boundaries put by this set of regulations, laws and policies (North, 1991; Meadowcroft, 2009; Olsen, 2009). The fact that institutional change is hard to steer, makes it difficult for stakeholders to innovate beyond the boundaries set by the formal institutional framework (Mahoney & Thelen, 2010; Walsh, 2012; Edquist, 2013). It is thus hard for stakeholders to execute pilots with hydrogen energy that do not fit within the current formal institutional framework. This is an inherent issue to innovation; formal institutional frameworks are fundamentally always lagging behind in relation to the technological state of development of new innovations related to energy supply (Edquist, 2013). Figure 3.3 summarizes how formal institutions and informal institutions shape the institutional framework that determines the acting space for stakeholders, and how the formal institutional framework can be changed in the political arena

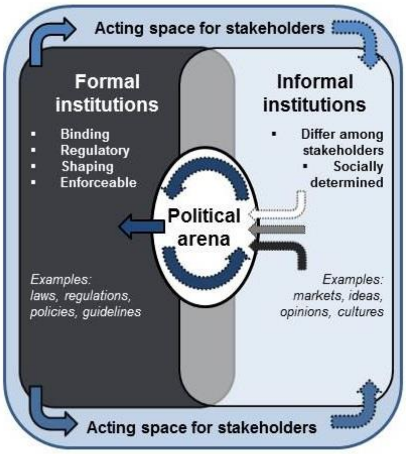


*Figure **3.3:** The interrelationships between informal institutions, formal institutions and the acting space for stakeholders (synthesised after North, 1991; Meadowcroft, 2009; Olsen, 2009; Kim, 2011; Edquist, 2013 by the author of this study).*

3.3.6 Decentralisation in Dutch energy planning

In the Netherlands, many planning tasks concerning the energy supply system for the built environment have been decentralised by the national government towards regional governments. This results in difficulties for implementing national energy sustainability interests at local levels (Savini, 2013). In the Netherlands, the energy transition in the built environment is often seen as a matter in which the municipal and provincial governments have a key responsibility responsible rather than the national government (Verbong & Geels, 2007; Meadowcroft, 2009). This results in an increased dependency of the national governments on the capacity of municipal and provincial governments (Savini, 2013). And although decentralised authorities are usually more capable of incorporating the specific local circumstances into policy (Zuidema, 2016), it is certainly not always guaranteed that decentralised authorities are able to take the responsibility to prioritise the policy domains decentralised by the national government in the way desired by the national government (Nadin & Stead, 2008).

The main reason is that the decentralisation of responsibilities is often not adequately accompanied by the corresponding resources, which restricts the capability of decentralised authorities to undertake action (Gupta, 2007). Moreover, the vertical integration of the energy planning system did not make decentralised authorities able *'to steer local authorities in the desired direction'* (Savini, 2013, p. 1594). According to the Netherlands Environmental Assessment Agency (in Dutch: *Planbureau voor de Leefomgeving* (PBL)), several municipalities face difficulties in allocating adequate resources and finding their exact role in the energy transition in the built environment (PBL, 2017). As the energy transition in the built environment takes place in a complex and uncertain context, it might be expected that regional governments will not always have enough knowledge and resources (both human and financial) to execute the transition (Gupta, 2007).

Additionally, decentralisation of energy transition management responsibilities often results in fragmented policy outcomes among decentralised authorities. To accelerate the energy transition in the built environment, however, Gupta (2007) argues that an integral and coordinated approach is required, in which both the national and the decentralised authorities have a key position but have different roles in different phases of the transition. The Netherlands is currently facing difficulties in finding the balance between the national and decentralised authorities' responsibilities, which leads to a fragmented policy regarding the energy transition in the built environment at both the local and national level (PBL, 2017). Locally, decentralised authorities may be in need of support of the national government for facilitation of hydrogen energy applications for the built environment.

3.4 A multi-level perspective on governance of the energy transition in the built environment

3.4.1 Multi-level perspective

The transition towards a sustainable energy supply system for the built environment can be seen as a systemic change in the socio-technical system of society, as argued in Sections **1.1** and **3.2**. The socio-technical system has multiple levels on which change can be induced. In order to analyse these changes on multiple scale levels, the multi-level perspective by Geels & Kemp (2000) can be used to conceptualise the different kinds of change that happen on these levels (Kemp & Rotmans, 2004). This perspective (Figure **3.4**) distinguishes between *'three levels of heuristic, analytical levels'* (Geels & Schot, 2007, p. 399): niches, socio-technical regimes and the socio-technical landscape (Van der Brugge et al. 2005), whereof the regime level is the most important level in a transition (Geels, 2011). Analysing this perspective offers insights in what levels and what kind of stakeholders are influential in a transition towards hydrogen energy applications as a means in the energy transition in the built environment.

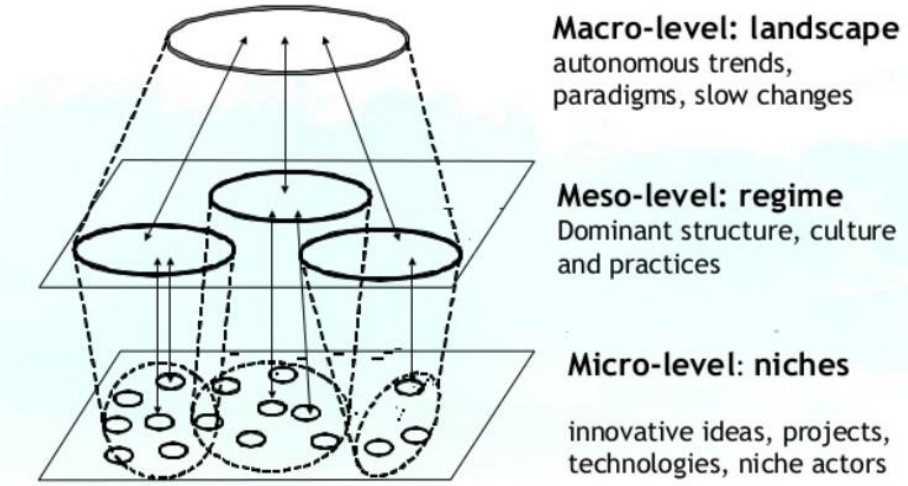


*Figure **3.4**: Multi-level interactions, edited from Geels & Kemp, 2000 (in Loorbach, 2007).*

Landscape level

The socio-technical landscape can be seen as the wider context wherein the energy transition in the built environment takes place (Geels, 2011). The landscape is determined by large scale and slow developments, found in e.g. culture and (scientific) paradigms. The current paradigm is that the built environment's energy demand is fulfilled with electricity and heat produced by combusting fossil energy sources (coal, natural gas and oil) on a controlled basis to secure energy supply. As argued in Section **3.2,** the actions needed to address these issues require fundamental changes in both the physical and institutional systems. Such a change in culture takes time, which means that the landscape has high influence on the speed of a transition. Changes in paradigms and cultures, cascade to the regime level.

Regime level

At the regime level (formal and informal) institutions and norms are established based on shared beliefs and assumptions. This level is the most difficult in terms of enforceable change because the regime level is occupied with (governmental and non-governmental) organisations and institutions that strive to optimise the current system (Rotmans et al., 2001). Strategies are focused on "optimisation and protecting investments rather than system innovation" (Van der Brugge et al., 2005, p. 167). Current policies are focused on optimizing the current system and based on ensuring energy security, economic feasibility and (local) environmental sustainability, but not necessarily in this order. Until recently, the lack of a (perceived) business case made investors and governments reluctant to really make the shift; there was less urgency to dramatically innovate for a new system. For this study, it is most relevant that the regime level can be considered to be the most important level (Geels, 2011), since stakeholders at the regime level are able to translate long-term landscape visions into concrete plans and projects with a short-term focus.

Niche level

At the niche level new innovations and technologies are developed by individual stakeholders like individual companies and inventors. These technologies are a significant departure from the status quo and are aimed at systems innovation. Entrepreneurs guide start-ups and spin-offs that develop new technologies (Geels, 2011). For example, Bekaert and Holthausen can be seen as driving entrepreneurs behind hydrogen technology (TKI Nieuw Gas, 2018) who guide new innovations into practically and economically feasible applications. Their aim is to have their new technologies be implemented eventually at the regime level, replacing or complementing old technologies. Geels (2004) argues that although niches are rooted in technology, it is the interaction with society that makes them relevant. Not every niche will reach the regime level in the end, but the niche level is where the transition starts (Elzen et al., 2004).

3.4.2 Exploration and exploitation at the regime level

The multi-level perspective provides insight in what kind of stakeholders are most relevant for this study. These are the regime level stakeholders, who are involved in tactical governance activities, interest driven, making mid-term projects, plans, institutions and regulations and additional are in the first place concerned with optimisation of the current state of the system. (Van der Brugge et al., 2004, Rotmans et al., 2001). However, the conservative attitude of regime-stakeholders seems to contradict the search for crucial niches (status-quo vs. innovation), but at the same time regime-stakeholders are crucial to overcome the challenges mentioned in **Chapter 2** and Section **3.3.** Regime-stakeholders can shape institutions which can facilitate society with the right institutions to increase trust, involvement and experience with hydrogen energy applications for the built environment (Duit & Galaz, 2008; Meadowcroft, 2009; Walsh, 2012).

So, the regime level can withhold a transition but at the same time is crucial for the development of this transition. The distinction between exploration and exploitation is useful to express the attitudes of the stakeholders at the regime (Duit & Galaz, 2008). Exploitation expresses the degree of activities of a stakeholder in which it seeks for refinement and efficiency of the current system to reduce costs and increase production. Trust and cooperation between stakeholders in a governance system is needed to increase exploitation mechanisms (Duit & Galaz, 2008). On the contrary, exploration expresses the qualities of a stakeholder to reflect and evaluate current activities, but more importantly, it involves activities of testing and experimenting with new forms of governance practices, like learning-by-doing processes. These explorative activities resonate perfectly with the quest for new niches, which are also most of the time trial-and-error processes (only few niches make it to a new regime). Additionally, exploitation processes are more costly and require knowledge and resources but are of high importance for the penetration of niches into the regime, such as hydrogen energy applications for the built environment; governance stakeholders with limited resources are often characterised by little capacity for exploration. Hence, for the transition to accelerate, rigid regime level stakeholders need to become more explorative by stimulating innovation, but are in reality more exploitative due to its wish to keep the status quo (Van der Brugge et al., 2004; Duit & Galaz, 2008; McDowall, 2012). To overcome barriers for implementing hydrogen energy applications as a means of energy supply for the built environment, to foster niches and to influence the regime, all require a high degree of citizen and stakeholder involvement (Duit & Galaz, 2008; Kemp & Rotmans, 2004).

It can thus be argued that decentralised authorities are most suited for explorative activities, given their proximity to society (Rotmans et al., 2001). However, at the same time, these decentralised local authorities are expected to be less capable of dealing with the complex objective of implementing hydrogen energy applications into the energy supply system for the built environment. As exploration requires a lot of resources, this is also conflicting with the need for more explorative stakeholders in the transition towards a sustainable energy supply system in the built environment (Duit & Galaz, 2008), also see Section **3.3.5.**

3.5 Transition management in the energy transition in the built environment

3.5.1 Transition management activities

It has been argued in the last sections that regime level stakeholders are able to foster change, and therefore regime level stakeholders are of particular interest for answering the research question of this study. By positioning all stakeholders who are involved in a multi-level perspective, transition management offers insights in what activities have to be executed by these regime level stakeholders. Transition management is an approach to manage, guide, mobilise and accelerate social innovation by coordinating multiple stakeholders at different levels (Loorbach, 2010). Transition management is most needed in the first two of the four (or five, when following Rogers (2010)) phases, in which niches need to co-evolve with other developments in a dynamic environment to later infiltrate the rather rigid regime (Rogers, 2010). Within a transition management framework, four different governance activities are distinguished, each leading to a further degree of change (which is considered to be the ultimate goal of transition management):

- *Strategic activity at landscape level:* The transition arena is established, wherein frontrunners are gathered in a network. Long-term visions are developed: goal formulation, anticipation and sense of urgency of the transition.
- *Tactical activity at the regime level:* Steering activities to determine the transition agenda. Long-term visions of the strategic level are translated into concrete mid-term focused plans and projects (incl. barriers, scenarios and transition paths).
- *Operational activity at the niche level:* Experiments with new innovation are executed with a short-term focus, regarding “societal, technological and institutional practices that introduce […] new structures, routines and stakeholders” (Loorbach, 2010, p. 170).
- *Reflexive activity:* this is an ongoing and very important element of transition management. Here the progress of the transition is monitored and evaluated, and the process of transition management itself is monitored. Questions like how far the system is changing and the successfulness of policies are set out at the tactical level and experiments at the operational level.

Although all these activities are important to achieve the facilitation of hydrogen energy applications into the energy transition in the built environment, the tactical activities associated with the regime level stakeholders are the main subject of this study. These stakeholders are able to foster change by undertaking these activities. Reflexive activities, which include learning processes (like learning-by-doing), are needed to overcome the barriers of experience, trust and acceptance that are often experienced by regime level stakeholders and are therefore also very important. Adding to that, operational activities are crucial for the emergence of the niches that are the visible symptoms of change (Elzen et al. 2004; Loorbach, 2010).

3.5.2 Energy transition management for the built environment in the Dutch planning system

Remarkably, the multi-level perspective, transition management and the theoretical division between the socio-technical landscape, the socio-technical regime, and niches resonate quite strongly with the spatial dimensions within the Dutch energy supply planning system. The national government sets out the strategic long-term visions and is bound to execute and defend the nationwide interests (Rijksoverheid, 2018a) and is thereby partly steered by the EU (European Commission, 2010). These activities of the national government are set out in the National Spatial Strategy and the Energieagenda (Rijksoverheid, 2016b), and comply with the activities of the strategic landscape level: a long-term focus on large scale vision with a sense of urgency (Nadin & Stead, 2008; Rijksoverheid, 2016b). The provinces, then, seem to match with the regime level stakeholders, where tactical governance activities take place. Especially the strategic vision (Dutch: Structuurvisie) can be seen as a translation of national interest and vision into regional visions and more tangible plans and projects, with a mid-term focus of 10 years.

Wind energy projects, for example, are drawn out in the provincial Strategic Vision Documents, while they are regional translation of the national Structure Vision for Onshore Wind Energy and the National Spatial Strategy. This translation from national to regional level and the mid-term focus matches with the tactical activities described above (Loorbach, 2010). Additionally, the provinces play a crucial role, as regime level stakeholders, which are influential for designing institutions that are useful for overcoming barriers to create room for niches. Nadin & Stead (2008) even hypothesise that the central government is in favour of letting provinces and regional TSOs take a key role in energy and spatial policies. In practice, these roles are also attributed at least partly to municipalities (Needham, 2005; Rijksoverheid, 2018d).

The similarities between the niche level and municipalities are significantly less clear, however. It makes no sense to argue that municipalities are driving forces behind niche developments. On the contrary; municipalities formally tend to play a similar role as the provinces do, just on a lower scale level. Formally, local initiatives have to be aligned with provincial ambitions (Rijksoverheid, 2014). This alignment can be seen as a translation from a regional vision towards local action, as this matches with deriving operational activities from tactical activities in transition management (Loorbach, 2010). However, in practice, municipalities can be involved with innovative projects in terms of financing and exposure they are involved in executing projects that involve sustainable innovative niches. For example in the case of the hydrogen-heated new development project Nijstad-Oost in Hoogeveen (Gemeente Hoogeveen, 2018a).

Furthermore, there is an overlap in stakeholders and the activities they perform at the different levels of transition management, which is especially clear for the energy transition in the built environment context. For example, Verbong & Geels (2007) argue that the Dutch Ministry of Economic Affairs and Climate Policy is an important regime level stakeholder in the transition towards sustainable energy production. Simultaneously, the ministry was involved in the production of so-called decentralised Combined Heat and Power plant (CHP) at the local level at the time that changes in the landscape stressed the consequences of climate change (Verbong & Geels, 2007). Van Doren et al. (2018) also stress the importance of this overlap in order to facilitate the scaling-up of low-carbon initiatives.

In this way, the national government is involved at all three layers of the transition; the macro long-term strategic vision at the landscape level, the tactical plans to implement these long-term vision at the regime level and finally the niches they induce e.g. in collaboration with major players in the energy sector. Consultancy firms like Royal HaskoningDHV could also be involved in every level as a consulting partner to support governmental parties or come up with innovative (policy) niches. Table 3.1 visualises the distribution of stakeholders over the levels of the energy transition.

Table 3.1: *Overview of stakeholders involved in the energy supply planning system, from a multi-level perspective in the Dutch planning system, divided by the systemic levels of transition theory.*

Systemic level in transition theory	Stakeholders in the Dutch energy supply planning system
(Socio-technical) landscape level	European Union
	National government ▪ Ministry of Economic Affairs and Climate Policy (EZK) ▪ Ministry of the Interior and Kingdom Relations (BZK)

	▪ Ministry of Infrastructure and Water Management (I&W)
	Energy companies
	Society
(Socio-technical) regime level	National government
	▪ Ministry of Economic Affairs and Climate Policy (EZK) ▪ Ministry of the Interior and Kingdom Relations (BZK) ▪ Ministry of Infrastructure and Water Management (I&W)
	Provincial and municipal governments
	Consultancy companies
	Energy companies
	TSOs
	Society
Niche level	Provincial and municipal governments
	TSOs
	Energy cooperatives
	Appliance developers
	Consultancy companies
	Conscious individuals

Summarising, this section suggests that the desired goal is that stakeholders at the regime level become more explorative which is needed to foster niche developments rather than becoming exploitative, which is in line with the way of reasoning of Duit & Galaz (2008). It is important to acknowledge the fact that decentralised authorities usually have limited resources and knowledge in order to be capable to actually do so (Van Doren et al., 2018) and to be aware that the acting space of stakeholders at all governance levels is limited. This has consequences for their ability to facilitate niche developments. As the table above shows, the reality is rather complex, though: many stakeholders at the regime level are willing to do so but seem to be constrained by the regime they (at least partially) constructed themselves. While this often leads to frustration, it might also lead to positive synergy; increased awareness of the regime limits increases the willingness to adjust these limits to their new needs and might, as such, accelerate regime level changes.

3.6 Conceptual framework

In the previous sections, a set of theories and concepts that are relevant to understand governance of sustainable innovative niches in a complex governance context were discussed. A short overview is provided below:

- **Chapter 2:** Energy transition in the built environment; introduction to hydrogen energy applications and alternatives;

- **3.1**: Diffusion of innovations; hydrogen energy applications framed as a sustainable innovation;
- **3.2:** Hydrogen energy applications as a niche in the energy transition in the built environment;
- **3.3:** Institutional challenges to facilitation of hydrogen energy applications in the built environment;
- **3.4:** Multilevel governance perspective on the energy transition in the built environment; decentralisation of planning responsibilities;
- **3.5:** Transition management and specifically the role of the regime level therein.

The combination of these theories, concepts and ideas results in the conceptual framework shown in Figure **3.5**. In this section, the conceptual framework is being discussed in detail. The main phenomenon under research is the [facilitation of the] **sustainable innovative niche** of **hydrogen energy applications** for the **built environment. Diffusion of innovations** provides a theoretical perspective on the market development of such niches; the various hydrogen applications have different degrees of market readiness and investment costs. From a **transition theory** point of view, this is one of the niches that struggle for a break-through in the **energy transition.** The energy transition is taking place in a **complex** and **uncertain** context, because it is concluded that the relationships between energy sources, energy carriers, energy infrastructures and energy stakeholders will increase in number and interdependency. Because of these **opportunities and challenges, stakeholders** are reluctant to invest, both financially and politically. Stakeholders who are willing to change balance these opportunities and challenges. From a **transition management** perspective on the energy transition, the **regime level** should be regarded the most important level for niches to come to a break-through; **regime level stakeholders** are concerned with **tactical governance activities**, which have both an **exploitative** (a tendency to optimise the **landscape** (current system)) and an **explorative** (a tendency to look for new, promising developments) **nature.** On the **meso level** of governance, **decentralisation of planning responsibilities** to regional authorities is taking place. One of the niches that are currently being explored is the hydrogen energy applications niche. Once the regime level of the energy transition in the built environment considers that opportunities outweigh challenges for facilitation, hydrogen energy applications might penetrate into the regime level and, consequently, into the landscape level.

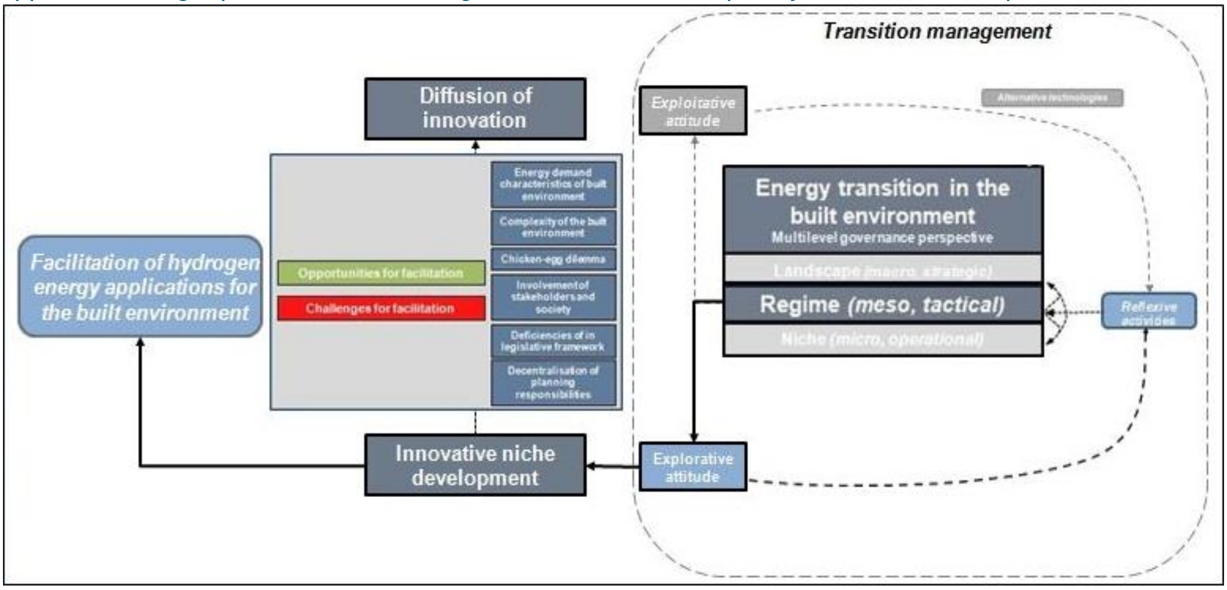


*Figure **3.5:** Conceptual framework for this study. This model conceptualises how hydrogen energy corporations could be facilitated by regime level stakeholders in the energy transition in the built environment by applying an* *explorative attitude towards the opportunities and challenges within their acting space, and conducting continuous reflexive transition management activities, based on the literature review in Chapters 2 and 3.*

The sections and the conceptual framework shown above provide a preliminary, theory-based answer to sub-question 4 (*How can stakeholders responsible for the regime level of the energy transition in the built environment be influenced and changed in the Netherlands?).* The patterns of action of regime level stakeholders can, apart from top-down pressure from the landscape level, be changed by the operational activities executed by bottom-up niche developments that gain momentum. At the regime level itself, stakeholders that apply an explorative attitude towards such niches are a prerequisite for such change if their actions are not directed by the strategic activities of landscape level stakeholders (Duit & Galaz, 2008). A continuous process of reflexive activities (learning processes, monitoring, pilots) is needed in order to increase trust and acceptance, both among the regime level stakeholders and society as a whole, which contributes to overcoming governance-related challenges (Kemp & Rotmans, 2004). Additionally, regime level change is fostered by collaboration of a diversity of stakeholders; government authorities, transmission system operators, market stakeholders and research institutes. They are needed all: authorities to create legal opportunities and acceptance, transmission system operators to adapt the networks to changing demands, market stakeholders to acquire knowledge and expertise and academia for further expansion of knowledge and R&D (PBL, 2017). In the first phases of the transition however, decentralised authorities (municipalities and provinces) have a key role in (Rotmans et al., 2001; Nadin & Stead, 2008). They have the ability to translate strategic visions of the national government (and, indirectly, the EU) into concrete, local policies with a spatial basis, to mobilise other stakeholders and to facilitate and stimulate bottom-up niche developments and to create synergy between different initiatives.

The conceptual framework mainly functions as a summary on how all concepts of the previous two chapters are related to each other, and offers a tool for the next empirical step of this study. It will be tested in the next stage of this study.

4 Methodology

This chapter elaborates on the research strategy and the corresponding methods that are used for this study (Section **4.1**), as well as the selection requirements for the case study that is investigated (Section **4.2**). Section **4.3** then elaborates on the collection of the data and provides an overview of the respondents and policy documents. Section **4.4** then elaborates on the analysis methods that have been executed to handle the gathered data. Consequently, the ethical questions involved with this study are being discussed in Section **4.5.** The applicability of a SWOT analysis, which is used as a tool to operationalise the opportunities and challenges identified in the documents and interview is then discussed in Section **4.6**.

4.1 Research approach

The theoretical framework outlined in **Chapter 3**, and more specifically, the conceptual framework outlined in Section **3.6** elaborate on and visualises how the niche of hydrogen energy could be facilitated by regime level stakeholders in the energy transition in the built environment. Regime change is fostered by the presence of niches, but the regime is responsible for facilitating such niches to upscale. The facilitation of a niche is being determined by the degree to which the niche's opportunities exceed their challenges, and this is development is greatly dependent on its complex context. This has implications for the research approach and research methods that should be applied to a research problem.

4.1.1 Single case study approach

The complexity of the research problem necessitates a research approach that is able to investigate the facilitation of hydrogen energy applications for the built environment within the energy transition context in an in depth manner. To gain such in-depth insights, an approach that incorporates the opportunity to investigate and understand complex phenomena in their context is needed (Baxter & Jack, 2008; Clifford, 2012; Yin, 2015). Although there are many research approaches that would work well to find meaningful answers to the research question, a qualitative case study approach is the preferred strategy to deal with the research problems regarding the limited amounts of time and financial resources. The main research question (*How could hydrogen energy applications for the built environment be facilitated by regime level stakeholders in the energy transition in the built environment in the Netherlands?)* is a good example of a research question that justifies such a case study approach (Yin, 2003). A well-executed case study approach research is capable of grasping the complexities of human experiences and interactions. The discipline of spatial planning therefore often uses qualitative research methods (Philip, 1998). It is important to understand that qualitative research like the case study approach used for this study is a non-value-free approach; this allows the inclusion of values and expectations to compare the roles of (groups) of stakeholders in the study, and of course that case studies fit with the research (Yin, 2003).

For this study, a single case is analysed to obtain meaningful answers to the research questions outlined in Section **1.2**. Case studies are examples from practice that are dealing with opportunities and challenges and therefore these are best suitable for acquiring the in-depth knowledge required to satisfyingly answer the research questions. In order to satisfyingly answer the research questions, the research method has to be aimed at gathering data about their (and their perception of other stakeholder's) views, perceived opportunities and challenges, ideas and visions, desires, possible miscommunications and lacks of alignment in visions, ideas and investments on hydrogen energy in the built environment. As well as about which stakeholders are involved in the case study, what their respective roles with regard to the case study are, which motivations (willingness) and competences (abilities) they have and what dilemmas they encounter in relation to the case study in particular. In order to gather such data, this research will be conducted on the basis of a document analysis to determine general developments and trends and a set of semi-structured interviews with multiple parties linked to hydrogen energy application experiments in the built environment, both on the regime and the niche level, and a document analysis to determine general developments and trends. This means that the research focuses on a single case study that is explored in depth rather than a large population that is superficially studied (Lieberman, 2005).

The results from the document analysis, the semi-structured interviews and the case study will be operationalised by using a tool for analysis (see Section **4.6)**

4.1.2 Document analysis

A document analysis is executed to determine the landscape level changes and ongoing developments within the energy transition in the built environment, in order to prepare the semi-structured interviews for the case study research. Document analysis provides a broad research base, if executed well (Baarda & De Goede, 2005). It is also a suitable research method to collect and analyse data from non-reactive sources (Reulink & Lindeman, 2005). Non-reactive sources are not prone to emotions or prejudice from the respondent, and therefore such sources can provide valuable, high-quality data Bowen (2009) and O'Leary (2014) argue that it is important to carefully think of the selection of documents and to be aware of their subjectivity. Therefore it has been chosen for to only analyse documents that have been issued by public authorities and renowned research institutes, as they should be assumed to be more trustworthy. The documents have been analysed to at the one hand build a knowledge base on the context of the transition under study for the interview analysis and at the one hand to identify the current stage of development of the energy transition in the built environment in the Netherlands.

4.1.3 Semi-structured interviews

The selected single case study is further investigated in depth by using semi-structured interviews with relevant stakeholders (policy makers, government officials and private parties). Semi-structured interviews are verbal interchanges where one person attempts to elicit information from another person by asking questions (Clifford et al., 2010). For such an interview, the questions are prepared beforehand. Semi-structured interviews, however, can unfold in a conversational manner offering the participant(s) the chance to explore issues and this places them apart from fully structured interviews where there is no room for exploration. According to Rabionet (2011) an interview is a powerful tool to gain insight in [the complexities] of human experiences and behaviour. The opportunity to explain the points made that is vested in an interview is of crucial importance since these explanations are the basis for creating a stimulating framework for stakeholders. The choice for a semi-structured interview format can further be explained by the arguments proposed by Gill et al. (2008), as it gives guidance on the specific topic but it also leaves room to explore and gain depth and insights that need explanation.

4.2 Selection procedure of case study

The case study for this study has been selected using a set of criteria that was set up in order to guarantee the quality and applicability of the data (Yin, 2003). These criteria have been derived from the theoretical framework that has been developed and outlined in **Chapters 2** and **3**. The theoretical focus of **Chapter 3** is on consequences of the contexts complexity on the institutional design and multilevel governance structure in transition management. The second-last section (**3.6**), showed that the regime level in a transition is important in the way that it allows niches to upscale and accelerate the transition, and that the niche level has a significant influence on that regime level, as innovations and changes usually emerge on this level. That results in three criteria:

- Sustainable innovative niches: the case should involve a concrete innovation and the development or facilitation of niches which are related to the energy transition in the built environment, due to the important role of sustainable innovative niches in the transition.
- Scale level: the niche development should have spatial consequences to an extent that it not only involves infrastructures within one specific building. This is crucial to acquire meaningful answers that are applicable to the built environment as an entity **(see Glossary).**
- Hydrogen energy applications: within the niche, there should be a focus on hydrogen energy. Without either innovation in the energy transition in the built environment or hydrogen, a conclusion that fits to the research question of this study will be impossible to provide.

A list of projects in the Netherlands that could have been potentially suitable for this study is provided in Table 4.1. Table 4.1 has been set up using project information obtained by a desk research in collaboration with consultants from Royal HaskoningDHV. The main stakeholders and policy-documents in the case of Nijstad-Oost/Erflanden, for example, were outlined after attending a meeting of the HYDORGREENN platform and exploration of the internet (Gemeente Hoogeveen, 2018a). The criteria of the involvement of niches and hydrogen are met because this project aims at innovating the energy supply of a housing district by using one or more hydrogen energy applications.

*Table **4.1**: Assessment of projects related to hydrogen energy applications for the built environment in the Netherlands that are potentially suitable for this study.*

Project	Main stakeholders (source)	Project phase	Involves sustainable innovative niches	Involves the built environment as an entity	Focus on hydrogen energy applications for the built environment
Nijstad-Oost/Erflanden, Hoogeveen	Gemeente Hoogeveen, Province of Drenthe, RENDO, New Energy Coalition, HYDRO-GREENN (Gemeente Hoogeveen, 2018a, DvhN, 2018)	Intention for 2018 , planned start: 2019	Yes	Yes	Yes
Stad aan 't Haringvliet	Gemeente Goeree-Overvlakkee, Province of South Holland, Stedin (Stedin, 2018)	Orientation phase started in 2017	Yes	Yes	Yes
H_2-natural gas mixture 14 Noorderlicht Apartments Nes, Ameland	Gemeente Ameland, Province of Fryslân, Eneco, GasTerra, Liander, Stedin, TNO, Kiwa Technology, Hanze Hogeschool (Duurzaam Ameland, 2018)	Started in 2008, test finished in 2012	Yes	No	Yes
H_2-natural gas mixture Bontweverij-Berkenkamp, Enschede	Klein Poelhuis, De Woonplaats, Gemeente Enschede, Tieluk (Tubantia, 2017)	Started in 2017	Yes	No	Yes
Green Hydrogen Economy Northern Netherlands *(programme)*	NIB, Province of Groningen/Drenthe/Fryslân, New Energy Coalition (NIB, 2017)	Started in 2017, intention for >2030	Yes	Yes	Partly
Solar-Power-to-the-People Rijnhuizen, Nieuwegein	KWR, Province of Utrecht, Gemeente Nieuwegein (AlliedWaters, 2017)	Intention for >2022	Yes	Yes	Partly
The Green Village, TU Delft, Delft	TU Delft, Gemeente Delft, National Government, DNV-GL, ERDF (The Green Village, 2018)	Testing site (since 2016)	Yes	Yes	Partly

It can be concluded from Table **4.1** that Nijstad-Oost/Erflanden in the municipality Hoogeveen is a suitable project to use as a case study for this study. The planned neighbourhood is the most advanced and concrete in terms of its stage in the planning process, and it is proposed to fulfil its energy demand with hydrogen using fuel cell technology (niche), while the existing neighbourhood is proposed to be a testing location for conventional combustion boilers that are able to use hydrogen, with a few houses running on 100% hydrogen to fulfil their heat demand and the rest of the neighbourhood running on a mixture of natural gas with hydrogen gas, in mixtures building up to 30% (niche), it involves a set of buildings and not one single building (scale level).

Additionally, the large majority of projects related to hydrogen in the energy transition in the built environment in the Netherlands involve more or less the same stakeholders (regional government authorities, TSOs and one or more research institutes and companies). Concluding, qualitative data is collected via the main stakeholders that are involved in the case study project that involves hydrogen energy applications in the energy transition in the built environment. These are assumed to be a representative for the other projects mentioned in the table as well. The exact features of and more details on the selected case study are provided in **Chapter 5.**

4.3 Data collection

4.3.1 Document analysis

As mentioned before under Section **4.1.2**, a document analysis is part of the research approach. The main goal of this document analysis is to identify the general developments on the landscape level of the energy transition in the built environment and the ongoing developments related to hydrogen energy applications in the built environment. These documents were found on the basis of a desk research, recommendations by the daily supervisor of Royal HaskoningDHV and some of the respondents that participated in the semi-structured interviews (also see Section **4.3.2**). The desk research and consultation resulted in Table 4.2, which includes the policy documents that are analysed. In addition to the general developments on the landscape level of the energy transition in the built environment, some policy documents are related to the establishment of the chosen case study. These documents are also included in the table.

*Table **4.2:** Overview of analysed documents that are used for the document analysis part of this study.*

#	Title *(translated title)*	Author	Year	Contents	Reference
1	Energy 2020. A Strategy for Competitive, Sustainable and Secure Energy	European Commission	2010	Shows the awareness of the landscape level for the need to change the energy supply system.	European Commission, 2010
2	Energieakkoord voor duurzame groei *(Energy Agreement for sustainable growth)*	SER	2013	Shows the Dutch implementation of Energy 2020 and acknowledges a transition perspective and the importance of stakeholder involvement	SER, 2013
3	Energieagenda: Naar een CO_2-arme energievoorziening *(Energieagenda: towards a CO_2-free energy supply system)*	EZK	2016	Sketches the main direction of energy policies in the Netherlands on a national level for the period until 2050.	Rijksoverheid, 2016b
4	Voorstel tot Hoofdlijnen voor	SER	2018	Shows the ambitions and substantialised proposals for a binding Climate Agreement that is to be devel-	SER, 2018

	een Klimaatakkoord *(Proposal for Guidelines for a Climate Agreement)*			oped in late 2018	
5	Inventarisatie (markt-)doorbraak technologieën voor een energieneutrale gebouwde omgeving	TNO	2017	Provides an analysis of the (perceived) market readiness of various sustainable energy alternatives for the built environment in the Netherlands	TNO, 2017
6	Net voor de Toekomst *(Grid for the Future)*	CE Delft	2017	Pones and elaborates on four possible scenarios (and their consequences) related to the infrastructure of the future energy supply system.	CE Delft, 2017
7	Contouren voor een Routekaart Waterstof *(Contouren voor een Routekaart Waterstof)*	TKI Gas	2018	Provides an overview of ongoing developments and initiatives related to hydrogen energy applications in the built environment and touches upon the conditions that are necessary for hydrogen energy applications.	Gigler & Weeda, 2018
8	Convenant energiebesparing gebouwde omgeving	Rijksoverheid	2017	Shows stronger ambitions for energy policy to the built environment.	Rijksoverheid, 2017
Case study-specific documents					
9	Proposal College of Mayor & Aldermen on subsidy request for H_2oogeveen	Gemeente Hoogeveen	2018	Shows the willingness of the municipal authorities to support the pilot area for hydrogen energy applications of Nijstad-Oost/Erflanden	Gemeente Hoogeveen, 2018a
10	Municipal Government Agreement 2018-2022	Gemeente Hoogeveen	2018	Expresses the goals and ambitions of the municipality of Hoogeveen for the coming government period.	Gemeente Hoogeveen, 2018b
11	Letter of Intention for Green Hydrogen Economy Northern Netherlands	NIB	2017	Expresses the willingness of a broad coalition of governments, scientists and innovative companies to invest in establishing a Green Hydrogen Economy in the Northern Netherlands.	NIB, 2017

4.3.2 Interviews for multiple case study analysis

According to Clifford et al. (2010), it is important to carefully think about the participants for semi-structured interviews. Longhurst (2010) notes that the respondents should be carefully chosen based on their experience regarding the subject and their involvement in the case study. The respondents interviewed for this study are selected with the help of the project managers and the internship supervisor from Royal HaskoningDHV and the document analysis. The consultant was interviewed first, followed by an academic and the project manager of Nijstad-Oost/Erflanden, who provided contact information to approach the other stakeholders. Based on this, the main stakeholders were selected. This method is also called snowballing. The selected stakeholders have been approached using phone and e-mail to determine the right contact persons and to make an appointment for an interview. Obviously, additional stakeholders are involved within this case-study, but their minor role in the project was neither expected not to influence a transition or the regime level, nor their experience is on the technical side of hydrogen applications rather than the governance side of the issue. Table 4.3 includes all the respondents that have contributed to this study.

*Table **4.3:** Overview of interviews and interviewed respondents.*

#	Date	Name of respondent	Organisation	Function	Place
R0	*May 26th, 2018*	*drs. M. Jager*	*Royal HaskoningDHV*	*Strategic consultant*	*Chopinlaan 12, Groningen*
R1	June 6th, 2018	prof. mr. dr. Catrinus J. Jepma	University of Groningen / New Energy Coalition	Academic researcher	Ubbo Emmiussingel 19, Groningen
R2	June 15th, 2018	ing. W. D. Hazenberg, MBA	HYDROGREENN	Chairman of HYDROGREENN	Euvelgunnerweg 12, Groningen
R3	June 18th, 2018	ir. B. Meijer	RENDO/N-TRA	Sustainable Energy Area Developer	Setheweg 1, Meppel
R4	June 27th, 2018	drs. K. Boer	Municipality of Hoogeveen	Project manager of Nijstad-Oost	Raadhuisplein 24, Hoogeveen
R5	June 27th, 2018	ir. J. Kolijn	Municipality of Hoogeveen	Project manager Sustainability	Raadhuisplein 24, Hoogeveen
R6	July 2nd, 2018	dr. ir. J.J. Aué	New Energy Coalition / Hanze Hogeschool	Researcher // Project manager	Zernikelaan 17, Groningen
R7	July 5th, 2018	ir. J. Scholte	Province of Drenthe	Project manager Sustainable Gas	Westerbrink 1, Assen
R8	July 23rd, 2018	drs. P. Nienhuis	Gasunie	Senior Advisor Energy Transition & Infrastructure	Concourslaan 17, Groningen
R9	July 26th, 2018	dr. G. van der Lee	TenneT	Senior Advisor Security of Supply	Utrechtseweg 310, Arnhem
R10	October 17th, 2018	ing. G.J. Evers	Province of Drenthe	Project leader Drenthe Energy Neutral	Westerbrink 1, Assen

For semi-structured interviews, there is no predefined list of questions (Reulink & Lindeman, 2005). This is necessary to provide room to the respondent to bring in own topics, examples and ideas. However, to structure the interview and to conceptualise the input, a list of topics and broad questions was set up separately for each interview. All interviews consisted of questions related to the general topic of hydrogen energy applications in the built environment, and the interviews with HYDORGREENN, RENDO, the municipality of Hoogeveen, the province of Drenthe and New Energy Coalition also explicitly focused on the case study (although the case study was touched upon in each interview). Many questions for all interviews were similar, but each interview also included at least one question that was specifically aimed at the particular respondent. This list, referred to as the interview guide, ensures that all topics are covered by the researcher. Constructing the interview guide is the most important step in using semi-structured interviews as a research method (Blumberg et al., 2011). The research goals outlined in **Chapter 1** and the theoretical framework (**Chapter 2/3**) are guiding while doing so. Taking the research goals and theoretical findings as starting points makes it easier to ensure that all relevant questions are being asked and a sufficient amount of data can be collected to answer the research question (Reulink & Lindeman, 2005). All interviews were conducted face-to-face and took between 45 and 80 minutes, with about 1 hour on average. The interview with the Municipality of Hoogeveen was a double interview, where two respondents of the same organisation were interviewed at the same time. As mentioned, an additional interview has been conducted to determine the large landscape changes. This interview is conducted with the internship supervisor, drs. Marc Jager, who is an expert and a big advocate in the field of hydrogen energy solution. An overview of the interview procedures, interview questions and their connection to the theoretical framework is included in **Appendix 3.**

4.4 Data analysis

While conducting qualitative research, the collected data are always subject to interpretation by the researcher and the data themselves are also a product of subjective interpretations that are based on the own perspectives and experiences of respondents and authors. It is important to be aware of that when analyzing the data that are produced while conducting qualitative research (Strauss & Corbin, 1998; Flyvbjerg, 2001).

4.4.1 Policy document analysis

The documents have been analysed by thoroughly reading them and marking relevant passages in the documents in Adobe Reader. These passages are referred to or quoted in this study wherever they are relevant, according to Table ***4.2.*** **Appendix 4** shows an example of such a marking.

4.4.2 Semi-structured interviews

All but one conducted interviews have been recorded for two reasons (with authorisation by the respondents, see **Appendix 3**): 1) to be able to retrieve the data in case this is necessary for what reason whatsoever and 2) to be able to analyse the interviews using interview data software. This study made use of ATLAS.ti, which is a software programme specifically designed to adequately analyse qualitative data. The recordings were started after the respondents gave permission to do so by signing the form of consent (**Appendix 5**) It is able to guide interview transcripts and it is helpful for further processing transcripts using coding mechanisms. These coding mechanisms provide the possibility to compare the different interviews in a structured way, in order to find connections between the statements made by the various stakeholders and organise these in a well-ordered manner (Cope, 2010) The coding scheme is included in **Appendix 5**. Before the interviews are conducted, the interview questions were drawn up on the basis of the elements outlined in the conceptual framework of Section **3.6.** These questions are connected with a 'family' (ATLAS.ti terminology for an overarching theme) that contains several codes connected to a specific concept. **Appendix 5** contains an overview of the codes and families and an illustration of how the process was executed in practice, by using screenshots.

4.5 Ethics

Ethics are a very important issue to take into consideration when conducting interviews. Interviews are held with people and their privacy and level of willingness have to be respected. Although this research is about a possible future transition and therefore it might be expected that no sensitive matters are touched upon, respondents who indicate that they are not willing to share all information this had to be (and is being) respected. Consequently, respondents who expressed a desire to remain anonymous are not being named in the analysis. Instead, *(S.N.)* is used as a replacement for the name of an anonymous respondent. However, none of the respondents expressed such a desire. All interviews are conducted in Dutch, as this is the native language of both the researcher and all the respondents. Whenever the interviews are referred to in this study, quotes are being translated as appropriate as possible to reflect the statements made by the respondents.

Furthermore, all respondents have been asked for approval for recording. Their permission to do so has been officially recorded by using a form of consent. This form is included in **Appendix 6.** Respondents were given the possibility to receive the published study. All the respondents received an introduction to the focus points of the study, in order to provide opportunities for preparing the interview. The respondents did not receive an extensive overview of the exact questions, which has deliberately chosen for in order not to over-ask the respondents.

4.6 Tool for operationalisation of the results

In the introduction of this study, it has been argued that there is lack of structural analysis on the opportunities and challenges for facilitation of hydrogen energy applications for the built environment. Therefore, this study aims at creating an overview of such opportunities and challenges in order to better understand what is needed to get hydrogen energy applications being facilitated by the regime level. Therefore, a tool is needed to present such opportunities and challenges in a well-ordered manner. The benefits and limitations of two tools of analysis are shown in Table 4.4. These are Social Cost-Benefit Analysis (SCBA) and the Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis. SCBA is a tool to assess the added social value of certain alternatives compared to their investments. It can be used to visualise which sustainable energy alternatives are viable in order to replace the current energy supply system. A SWOT is a *'strategic planning tool, used to evaluate the Strengths, Weaknesses, Opportunities and Threats involved in a project'* (Hay & Castilla, 2006, p.4).

*Table **4.4**: Comparison of SCBA and SWOT tools for presentation of opportunities and challenges (Hay & Castilla, 2006; Mouter, 2012)*

Tool for presentation	SCBA	SWOT
Advantages	▪ Practical tool for policy makers ▪ Clear overview of costs and benefits ▪ Objective tool to weigh arguments and investments ▪ Offers a tool for improvement of inefficient projects ▪ Transparent and traceable	▪ Rather simplistic, therefore easy to interpret ▪ Ability to visualise complex issues in a clear and easy-to-gasp way ▪ Provides a clear overview of opportunities and challenges on what strategy should be taken ▪ Functions as a tool for institutional reflection
Disadvantages	▪ Tends to involve high levels of uncertainty due to its future-oriented nature ▪ Social impact of issues has a weak profile in SCBA due to a tendency to measure in financial terms	▪ Tendency to generalise or over-simplify issues ▪ Often leaves room for interpretation of the reader ▪ Limited depth ▪ All issues have equal weight in visual presentation

The advantages and disadvantages shown in Table 4.4 advantages and disadvantages result in the conclusion that a SWOT analysis is more suitable for this study. A SCBA will results in more practical outcomes for policy makers, but due to highly complex and uncertain context of the energy transition in the built environment, the SCBA would be less useful to operationalise the even more uncertain results. Also the tendency of SCBA to measure in financial terms is problematic; there are limitations in time and means to adequately measure financial opportunities and barriers for hydrogen energy applications for the built environment. Therefore, a SWOT analysis is the preferred tool for this study. The limitations of a SWOT-analysis can be reduced by using only data from the interviews. Hereby, oversimplification is reduced. A SWOT analysis visualises the identified strengths, weaknesses, opportunities and threats of an issue in a SWOT-matrix. A conceptual visualisation of such a matrix is shown in Figure 4.1. The underlying principle of a SWOT-analysis is that the matrix is used as "input to creative generation of possible strategies" (Hay & Castilla, 2006, p.4) to make use of the strengths of the issue, reduce its weaknesses, exploit present opportunities and identify possible threats. These will be abstracted from the documents used for the document analysis and the semi-structured interviews.

A SWOT-analysis makes a distinction between internal and external factors. This suits focus on governance in this study. The internal strengths and weaknesses of the stakeholders at the regime level can be identified, which helps to come up with governance recommendations to facilitate hydrogen energy applications within the energy transition in the built environment.

*Figure **4.1:** Conceptual visualisation of the elements of a SWOT analysis. The clear distinction between external and internal factors makes SWOT analyses suitable for governance analyses (based on Hay & Castilla, 2006)*

5 Introduction to the case study

This chapter provides some relevant background information on the case study that has been selected in Section **4.2**, and it also provides an overview of the main stakeholders that are involved in this case study project.

5.1 History and ongoing developments in Nijstad-Oost/Erflanden

The municipality of Hoogeveen is located in the south of the Province of Drenthe (located in the North-Eastern Netherlands) and consists of a medium-sized town and a dozen of surrounding villages. In terms of sustainable energy supply goals, the municipality has the desire to be climate neutral (see **Glossary**) by 2040 (Gemeente Hoogeveen, 2018b). To achieve this goal, all new housing developments in the municipality have to fulfil their energy demand with sustainable energy alternatives (Gemeente Hoogeveen, 2018a, 2018b). The municipality of Hoogeveen currently aims to develop Nijstad-Oost, a small residential neighbourhood (80-100 residential units) immediately west of the existing neighbourhood of Erflanden (1030 residential units, built after 2000) and east of the former sand extraction location of Nijstad, which has now been converted into a recreational area. The municipality had the ambition to create synergy with the surrounding environments: *'When we started Nijstad-[Oost], it was our task to design a sustainable neighbourhood. [...]. Since I am a spatial planner, I am fascinated by the fact that new developments actually always completely destroy the existing landscape. Therefore I was thinking: we need to embed into the surroundings. And yes, if we conduct an intervention there, we should explore the opportunities to make it a sustainable energy engine for the surroundings'* (R4). Simultaneously, HYDORGREENN (a loose, informal network of technology-related companies, consultancy firms, TSOs and research institutes) was looking for pilots in each energy end-use sector (see **Glossary**) to develop concrete pilot projects to gain experience with hydrogen as an energy carrier (quote). HYDORGREENN established itself (bottom-up) to translate the NIB's story into concrete projects by willing market stakeholders and research institutes, who share the vision that hydrogen is a very important component of the energy transition and see clear future opportunities within their business for hydrogen as an energy carrier. With some coordination of the province of Drenthe. HYDROGREENN took note of the desire of the municipality of Hoogeveen. '[then] *Willem [Hazenberg, R2] said: 'as representatives from HYDROGREENN we want to look at number of pilot projects from three categories and those are mobility, industry and built environment. And then he said: yes, we actually do not have a pilot project for the built environment yet. And... Then I put forward that in Hoogeveen there is an initiative for a new sustainable neighbourhood.'* (R7)

HYDROGREENN thus emerged in reaction the initiative of the NIB (2017) to expand a green hydrogen economy in the Northern Netherlands (quote, NIB 2017), HYDORGREENN got in contact with the project manager of the municipality of Hoogeveen who is responsible for the developments in Nijstad-Oost. It fits within the wider objective of Drenthe (and the other Northern provinces of the Netherlands) to become a frontrunner in the field of renewable energy in general and hydrogen energy in particular.
After numerous consultations, a concept energy supply system was drawn up with the help of RENDO (the local TSO responsible for natural gas distribution), several technology-related companies and Royal HaskoningDHV (a consultancy firm). In a later stage, it was decided to also include the adjacent neighbourhood of Erflanden, as the municipality of Hoogeveen also has the desire to replace natural gas in the rest of Hoogeveen's housing stock and this *'created the opportunity to create more hydrogen demand'* (R2). The result was the appointment of the blue- and red-coloured areas on the map of Figure 5.1 as a pilot area for hydrogen energy applications in the built environment. In March 2018, a first subsidy request was submitted by the municipality and the first group of project partners from HYDORGREENN (Gemeente Hoogeveen, 2018a) under the name '*H_2oogeveen'.* Later, in the course of the summer of 2018, the consortium was enlarged to 27 parties (see **Appendix 7**).

Multiple types of hydrogen energy applications (see Section **2.2)** are proposed to be tested in the pilot area. First, the new residential units of Nijstad-Oost will use **fuel cell technology** (for at least their heat supply). As of November 2018, HYDORGREENN and the municipality of Hoogeveen are still investigating whether fuel cell technology should be applied on the level of the individual residential unit or on the level of the neighbourhood (in combination with a heating network. For Erflanden, hydrogen will be gradually admixed into the gas infrastructure to the extent of a 30% H_2 – 70% natural **gas mixture** by 2030. Additionally, a boiler producer and RENDO are proposing to replace some of the conventional boilers in the existing neighbourhood with 100% H_2-boilers in order to test **conventional combustion technology** with 100% hydrogen. The exact amount has yet to be decided upon, but *'the preference is more for a larger number than for a smaller number [than 50].'* (R2). There are also ideas for hydrogen-based ***energy storage technologies*** and local ***production*** of hydrogen, but these are not decided upon so far. For an overview of the testing site and its location in its immediate surroundings, see Figure 5.1.

*Figure **5.1**: Map of the pilot area for hydrogen energy applications for the built environment in its surroundings. Source: edited after Gemeente Hoogeveen (2018) and Google.*

5.2 Stakeholders involved in the development of Nijstad-Oost/Erflanden

This section provides an overview of the most important (groups of) stakeholders that are involved in the development of Nijstad-Oost/Erflanden. Not all stakeholders are mentioned individually because this is not considered relevant in the context of this study. The overview is based on the Proposal by the Board of Mayor and Aldermen (Gemeente Hoogeveen, 2018a).

HYDORGREENN

A loose organisation of 88 entities (as of July 2018) with various backgrounds (appliance developers, TSOs, energy companies, consultancy firms, research institutes, decentralised authorities and the Ministry) that is exploring opportunities to conduct pilots on the field of hydrogen energy. For Nijstad-Oost/Erflanden, HYDORGREENN develops the pilot for incorporation of hydrogen energy applications in the pilot area. All other stakeholders also participate in HYDORGREENN, to various degrees. For an overview of parties which are formally connected to HYDORGREENN, see **Appendix 7.**

All other involved stakeholders are active in HYDORGREENN. However, a few of these stakeholders are of particular importance for this study:

Municipality of Hoogeveen

Nijstad-Oost/Erflanden is situated within the boundaries of the municipality of Hoogeveen. The municipality is the initiator and land owner of the new housing development of Nijstad-Oost and the decentralised authority that is responsible for the implementation of the project.

Province of Drenthe

The municipality of Hoogeveen is situated within the province of Drenthe. The province mainly functions as a coordinative and facilitating stakeholder, who connected HYDORGREENN to the municipality of Hoogeveen and proposed the idea of hydrogen energy applications.

RENDO / N-TRA

RENDO is the local transmission network operator for natural gas distribution in the municipality of Hoogeveen and therefore the owner of the existing network of gas pipelines in Erflanden (and possible future ones in Nijstad-Oost). N-TRA is its subsidiary that anticipates on the future energy supply systems in its operating area.

Market stakeholders

The construction of the residential units and appliance development will be the responsibility of conventional market stakeholders, such as contractors and suppliers. Because the actual development of the neighbourhood has not yet started, their roles will not be further emphasised upon.

6 Results

In this chapter, the results of the document analysis and the semi-structured are presented. Each section is devoted to one of the six sub-questions outlined in Section **1.2.** In these sections, the collected data will be presented and analysed for the general topic of facilitation of hydrogen energy applications for the built environment and for the specific developments regarding the case study, based on the document analysis and the semi-structured interviews. In **Box 5**, it is explained how these data are being referred to. The sixth sub-question will apply an extensive SWOT analysis on the facilitation of hydrogen energy applications for the built environment in governance structure of the Netherlands.

Box 5: Referring to the results of different data sources

This chapter extensively refers to the results of the document analysis and the semi-structured interviews. As such, it is important to understand how these data sources will be referred to in the analysis.

- For the ***document analysis,*** 12 documents were analysed and marked in Adobe Reader (also see **Appendix 4**). In the next sections, the marked passages are mostly used as input and reference for the textual analysis. When direct quotations are included, these will be highlighted according to the following format: ''*Quote*'' (document, year, page number). Both integrated fragments and quotations are referred to following Table **4.2** on page 50.
- For the ***semi-structured interviews***, 11 people have been interviewed during 10 different interviews: 10 respondents were interviewed in interviews with a single respondent, while 1 interview was conducted with 2 respondents (also see Section **4.3**). These interviews have resulted in 9 extensive and coded transcripts; the interview with the internship supervisor from Royal HaskoningDHV has not been transcribed nor coded. **Appendix 3** shows the guidelines for these interviews. In the next sections, the transcripts will be extensively referred to. In case the statements of the respondents are integrated into the text, these will be referred to by concluding a sentence with (R#). Interesting, illustrative or otherwise relevant quotations are directly included into the text as a service to the reader. These are referred according to the following template: "*Quote*" (R#). The numbers of the respondents correspond with the numbers in Table **4.3** on page 51.

6.1 The potential of hydrogen energy applications in the future energy supply system for the built environment in the Netherlands

- This section presents the results to the sub-question: *What is the potential role of hydrogen energy applications in the future energy supply system for the built environment in the Netherlands?*

All documents and interview respondents argued that the position of hydrogen energy applications in the built environment will be dependent on the position of hydrogen in the wider future energy supply system. Therefore, first some attention will be given to the wider perspective that was outlined during the interviews before getting to the position of hydrogen energy applications in the built environment.

6.1.1 Hydrogen in the future energy supply system

Following the document analysis and the semi-structured interviews, there is broad consensus among stakeholders that hydrogen will become an important energy carrier in the future energy supply system. In the *Voorstel voor Hoofdlijnen van een Klimaatakkoord* by the Dutch Socio-Economic Council (SER), hydrogen is described as a key element of the energy transition (SER, 2018), and TKI Gas states that the potential of hydrogen as an energy carrier will on the long term outweigh the challenges related to it (Gigler & Weeda, 2018). The two most significant abilities of hydrogen as an energy carrier that are identified in the analysed documents are related to **energy storage** and **sector coupling.** In the visionary document *Contouren voor een Routekaart Waterstof,* TKI Gas summarises these potential contributions to the future energy supply system as follows: *'The production of hydrogen by electrolysis offers a flexible mechanism for the medium and long term to effectively utilise the enormous potential of wind and solar power. It fulfils a crucial system role. This mechanism can support the future electricity supply by buffering and storage of these renewable power sources, but it should be predominantly treated as an option to utilise wind* *and solar power to replace fossil fuels and raw materials. Furthermore, hydrogen offers a solution for the limitations that are connected to electricity transport. In the long-term future, large-scale import of sustainable hydrogen from areas with high potential for sustainable energy, especially wind and solar power, are interesting and probably necessary, as is evidenced by indicative calculations on the potential of hydrogen in different applications.'* (Gigler & Weeda, 2018, p. 7).

The ability of hydrogen to buffer renewable electricity contributes to solving the intermittency problem (Section **2.1**), which is seen as the most fundamental challenge to the energy transition (SER, 2013; Rijksoverheid, 2016b, SER, 2018). This was strikingly expressed by respondent 6 *'You cannot do it without [storage of renewable electricity]. It is a bit like the holy grail in the world of sustainable energy: […] There is more than enough renewable potential. It is just located at the wrong places. Efficient and cheap methods to store this potential would solve a great deal of the world's energy problem.'* (R6).

In an energy supply system in which fossil fuels and nuclear energy have no place anymore, an energy supply system in which hydrogen does not have a key role is hard to imagine due to these potentials for energy storage (CE Delft, 2017). In each of the four scenarios drawn up in their report *Grid for the Future* (2017), commissioned by the collaborating Dutch TSOs, hydrogen has a key role. One of the main conclusions of this report is: *'Hydrogen is essential for the future energy supply system; it […] enables us to [utilise] the potential of wind and solar energy as more than just electricity, but also to store energy.'* (CE Delft, 2017, p.10). The awareness among TSOs seemed to be a rather recent development, as a sustainable energy manager working for RENDO (a local TSO) expressed: *'What for us was most remarkable, and this was truly an eye-opener: the role of hydrogen. What kind of prominent role hydrogen will fulfil.'* (R3).

Hydrogen is also considered an important component of the future energy supply system because of its energy efficiency and relative easiness of transport (Gigler & Weeda, 2018). This advantage is shared with other molecule-based energy carriers (CE Delft, 2017; Gigler & Weeda, 2018).Transport of electricity is relatively inefficient and impossible to provide high power abilities without enormous investment costs: *'I am quite convinced of that* (hydrogen gets a prominent position in the future energy supply system) *For the very simple reason that hydrogen, as [a] molecule-based energy carrier, is much easier and cheaper to store. That is no difference of a factor two, but roughly a factor 5000. […]. Additionally, it is much easier, cheaper and more efficient to transport hydrogen. That is no difference of a factor two, but closer to a factor 20. The energy density is just much higher. […]. Consequently, the chemical sector needs molecules at the end. […] That also explains why many experts think that molecule-based energy carriers will remain the most important energy carriers, also in a sustainable energy supply system'* (R1).

It is argued by CE Delft (2017) that the exact position hydrogen will have is dependent on societal and political choices that will have long-term consequences (see Sections **6.3-6.6**). Crucial choices have to be made regarding the energy supply system of the future. Therefore, in the document analysis has been checked for the views and ideas (supra)national stakeholders have on this, and regional and local stakeholders who are involved in governing the energy supply system were asked to give their view on the role of hydrogen in the future energy supply system.

On the supranational scale level, the EU is aware of the opportunities hydrogen offers on energy applications, but it is argued in their long-term energy policy as well that this offers opportunities to further integrate the European energy markets: *'ambitious projects will be initiated [to further integrate the European energy market], like hydrogen use. These will prepare us for the massive inflow of small-scale, decentralised and large-scale, centralised production of electricity'* (European Commission, 2010, p. 19). (European Commission, 2010), which is confirmed by the Dutch national government in their *Energieagenda* (Rijksoverheid, 2016b).

The interviewed decentralised authorities acknowledge the key role of hydrogen in the energy transition as well, as hydrogen is seen as the only practically and financially feasible mechanism to buffer renewable energy sources (R4; R7), although they acquired this knowledge from their networks and are not actively studying it. The changing patterns of power generation also necessitate such a mechanism, both due to the technical needs, as well to limit investment costs by society and therefore it is important that decentralised authorities are also aware of the potential of hydrogen-based energy solutions.

For Gasunie and TenneT, hydrogen is one of the key focus points of their energy transition strategy. Gasunie considers this as important because their task is to de-carbonise their activities and to maintain the natural gas grid, which can offer an opportunity to balance irregular and unpredictable supply of renewable electricity: *'The energy carriers used by end-consumers, should have no net emissions by 2050. […]. One of the energy carriers that involve no net emissions is hydrogen. […] And our infrastructure could offer an opportunity to store hydrogen and to buffer renewable electricity production. […]. This is beneficial, as molecule-based energy carriers are much easier to store.*' (R8). TenneT considers Power to Gas technologies as crucial to be able to maintain the network in terms of costs and in terms of future needs, and therefore predicts hydrogen to be a key component of the future energy supply system: *'The […] proposed potential of renewable energy generation is five times as high as the current demand. That means it is necessary […] to find creative solutions to utilise that potential. And although electrification will happen to a large extent; within mobility, within the built environment, and we also consider to partly fulfil the heat demand of the built environment with electricity. This will be a challenge. We need to convert electricity into molecule-based energy carriers. To be able to [buffer and] transport this potential, but also because there will be more demand for chemical energy.'* (R9).

6.1.2 The position of hydrogen energy applications in the built environment

The document analysis and the interviews resulted in ambiguous findings on what position hydrogen as an energy carrier will obtain within the energy supply system for the built environment. The technological applicability of such applications is widely recognised and confirmed (Rijksoverheid, 2016b; TNO, 2017; Gigler & Weeda, 2018), but there seems to be very limited consensus on many institutional aspects related to implementation: *'It [hydrogen energy for the built environment] is a difficult question'* (R1); *'it is a complex puzzle.'* (R6). Many reasons for this lack of consensus among stakeholders were identified, but only reasons that relate to the findings of **Chapter 2** are described here. All others are addressed in Section **6.3.**

Other stakeholders see the technological potential, but see challenges regarding the limited supply of hydrogen and the availability of a wide range of other options for the built environment. For example in their *Energieagenda,* the Ministry of EZK (2016b) argues that *'the application of renewable gases in other end-use sectors [than the built environment] would be a more obvious choice – especially for transport and industry – because there are less options for sustainability in these sectors and supply is limited.'* (Rijksoverheid, 2016b, p. 69). CE Delft (2017) suggests that the degree to which hydrogen will be applied in the built environment will depend on what choices are going to be made, but argues that in every scenario hydrogen will also fulfil a role within the built environment. All respondents however argue that hydrogen energy applications could be a promising sustainable energy alternative, given the stocks are sufficient (R1; R2).

In visionary documents, hydrogen energy applications for the built environment are most often described as a long-term possibility for fulfilling heat demand: *'On the long term, hydrogen could replace natural gas to fulfil (low temperature) heat demand of houses and buildings.'* (SER, 2018, p 56). Also *Contouren voor een Routekaart Waterstof* (Gigler & Weeda, 2018) treats hydrogen as an energy carrier that is aimed to fulfil heat demand. Fulfilling electricity demand with hydrogen on the level of a household has hardly been elaborated upon during the interviews and in the documents, but is suggested to contribute to the efficiency of fuel cell technology on the level of a household (R2; R10). Some respondents also said to know about experiments with hydrogen as a medium for electricity storage in the built environment, although there seems to be a lack of agreement on what scale level this should be executed. Experiments with hydrogen-bromide flow batteries on the level of a single home are in a pre-planning stage now (R10). The respondents that represent a TSO are discussing opportunities for local storage of electricity by using power-to-gas technologies (R3; R9)

The ideas under what conditions in the built environment these hydrogen energy applications are most suitable, differ widely among the respondents. The analysed documents did not differentiate between different types of built environment, but the *Energieagenda* (Rijksoverheid, 2016b, p. 62) provided an important point of reference: *'In the first place, energy consumption should be reduced as far as possible, but that an optimal implementation of energy saving and sustainable heat supply (heating network, all-electric and/or renewable gas) could differ regionally or locally, which necessitates a customised approach'.* The *Voorstel voor Hoofdlijnen van een Klimaatakkoord* (SER, 2018) handles a similar way of reasoning, and also in *Contouren voor een Routekaart Waterstof* (Gigler & Weeda, 2018) it is argued that hydrogen energy applications for the built environment should be seen in the wider perspective, including alternatives.

These findings correspond with the statements made by the interview respondents: *'hydrogen [energy applications for the built environment should be seen] as an option to achieve a goal and not as a goal in itself'* (R6). The future energy supply system of the built environment is expected to consist of a range of sustainable energy alternatives (R3; R9), and RENDO states that they *'expect hydrogen to fulfil a significant role in space heating in the* future' (R3). Hydrogen energy applications for the built environment are one of these, next to, amongst others, heating networks, solar boilers, all-electric heat pumps and geothermal energy that will constitute the '*palette of sustainable energy options for the built environment'* (R4). For which types of built environment hydrogen energy applications could have the biggest potential, then, two main different lines of thinking could be identified from the semi-structured interviews.

R1 argued that hydrogen energy applications would first be implemented in new neighbourhoods and buildings with high energy consumptions, as these are easier and/or more cost-effective to adapt: *'It works for big buildings with high energy consumptions, like factory halls, hospitals […] and schools. In those situations, I expect hydrogen to come first. And new neighbourhoods. And the stock of older buildings, with all due respect, but I think those will fulfil their energy demand with natural gas, for the time being.'* (R1). The project leader for sustainability of the municipality of Hoogeveen shares a somewhat similar opinion (R5).

Adherents to the second line of thinking see opportunities for hydrogen in situations where other sustainable energy alternatives, such as electrical heat pumps and heating networks are neither technically possible nor financially feasible, which are predominantly existing buildings. This is also a conclusion made by TKI Gas (2018): *'For the existing stock of buildings, these options [heating networks and heat pumps] are less simple, however. Here lies an enormous challenge […]. Therefore, opportunities to replace natural gas with a sustainable type of gas are being investigated. […]. The replacement of natural gas by green gas is an option, but (climate neutral) hydrogen is also coming into the picture*.' (Gigler & Weeda, 2018, p. 38). Potentially suitable situations might include monumental buildings, old inner cities and sparsely populated rural areas: *'However, there are many situations in which large-scale electrification is not possible. Think of old inner cities […]. But also rural areas; rural areas are sparsely populated, which will probably result in large-scale electrification becoming far too expensive. Additionally, such areas have a housing stock that is difficult to electrify. Therefore, I expect that sustainable gases have a role in such situations'* (R6). Gigler & Weeda (2018, p. 42) go even further by stating that *'the costs of adapting the natural gas grid per house seem to be cheaper then to provide the house with an all-electric heat pump […]. Therefore, it could be considered that 'all-electric options should be applied where possible, and that otherwise hydrogen [energy applications] should be considered as an alternative'* in their report *Contouren voor een Routekaart Waterstof.*

Gasunie also mentioned the feasibility of other sustainable energy alternatives as a determinant for situations in which hydrogen energy applications could be a suitable option: *'[Heating networks]. For small villages or in the countryside, these will not be feasible. The reason why one should want an energy carrier that consists of molecules in such situations is that such energy carriers are able to deliver a much higher power level to the house. […] Therefore, heating by the means of an electricity-driven heat pump requires the house to be insulated very well. As long that didn't happen, society will need a molecule-based energy carrier. Or heating networks. […] Hydrogen is such an energy carrier'* (R8).

6.2 Current facilitation level of hydrogen energy applications for the built environment by regime level stakeholders

- This section presents the results to the sub-question: *What is the current phase of the energy transition in the built environment in the Netherlands, and what is the current position of hydrogen energy applications therein?*

Although the urgency and necessity of an energy transition in the built environment are widely acknowledged (European Commission, 2010; Rijksoverheid, 2016b, SER, 2018), it is not yet determined what the current phase of this transition is. In order to determine the governance-related opportunities and challenges on the facilitation of hydrogen energy applications, a deeper understanding of the current phase of the transition is required. Identifying the current position of hydrogen energy applications within this transition is lacking so far and provides us with a useful context to the result.

6.2.1 The energy transition in the built environment in the Netherlands

The landscape vision of virtually all stakeholders involved with the energy transition in the Netherlands is clear: the built environment should have no net emissions by 2050 and this goal is expected to be met (SER, 2013; SER, 2018). A transition perspective on this challenge has also been adopted, as it acknowledged that the creation of a sustainable energy supply system for the built environment requires fundamental changes in the socio-technical system (SER, 2013) which *'will take decades to steer the energy supply system towards a […] more sustainable direction, but [ambitious goals and] policies should be designed now in order to successfully finish this task; […] the decisions that are made now will have consequences for the next 30 years.'* (European Commission, 2010, p.2). The *Energieagenda* drawn up by the Ministry of EZK (2016b, p. 5) summarises it as follows: *The transition towards a low-carbon energy supply system requires major efforts […]. The task is complex: timely development and availability of sustainable energy alternatives, major investments […] and - in our densely populated country – continuous balancing the spatial effects. Above all, the energy transition is also a social challenge, as it directly interferes in the daily lives […] A transition of this size only takes place if the energy supply also will be affordable, reliable and safe.'*

The documents tend to point out what approach is needed rather than what the current situation is. The European Commission is asking for *'special attention to the sectors with the highest potential for increasing energy efficiency […]. Measures must be adopted to significantly accelerate the pace of renovation with the use of energy-efficient technologies.'* (European Commission, 2010, p. 7). This perspective is also recognised in the Climate Panels for a binding Climate Agreement: *'We are on the eve of a major renovation. The transformation of our 7 million houses and 1 million buildings [...]. Such a renovation is a huge task. But we have until 2050. We can do this, provided we tackle it in a structured way and improve all preconditions.'* (SER, 2018, p. 30). According to the *Convenant Energiebesparing Gebouwde Omgeving* (VNG/NBN/BNL, 2017, p. 1) an integral approach is needed: *'[…] to accelerate the energy transition in the built environment, there is a need for solutions that are accessible, affordable, scalable and efficient. This requires local customisation and an integral approach'.*

Even though a cross-sectoral, integrative approach is called for in the documents, the interview respondents do not all recognise this perspective in the current energy transition in the built environment. R9 (TenneT) argues that the energy transition is currently being too much approached from a sectoral perspective, which could result in solutions that are far below optimal: *'From my expertise, I think it is a missed opportunity that within the current climate negotiations, the approach was far too sectoral. Right? There is the pillar of the built environment, and then there is the pillar of electricity production… The advantages of synergy that could be achieved there, they will likely result in sub-optimal solutions, in my opinion.'* (R9)

The earthquake-related problems induced by the extraction of natural gas in the Province of Groningen are seen as a strong accelerating development that increases the awareness of stakeholders that the transition is needed (R1; R8). According to many respondents connected to TSOs, however, such developments could cause a situation in which speed prevails over cleverness on the long term (R3). TenneT argues that such developments have an impact of the consistence of national policies: *'Well, the Groningen gas. Yes. That suddenly became acute by [the decision of] Minister Wiebes, right? […] We need to know what we could expect from the government. That avoids situations in which we get behind the facts.*' (R9).

The visionary and policy documents have resulted in a more explorative attitude among stakeholders that are involved with the energy transition in the built environment. For example, the obligation to connect homes with the natural gas grid was abolished in 2018 (Rijksoverheid, 2016b; Rijksoverheid, 2018) and provinces and municipalities are implementing measures and instruments to entice stakeholders to invest in making their real estate assets more sustainable (R4/R5; R7/R10). However, decentralised authorities experience a lack of resources (both legal and financial) to support new developments (R4/R5). An interview respondent connected to a Dutch province stated: *'[…] I think the National Government should provide more resources. The magnitude of this task is tremendous. And also the regulatory framework; that should be adapted to the transition.'* (R10). This is also acknowledged in a position paper by the Vereniging Nederlandse Gemeenten, the collaborating Dutch TSOs and the business organisation for construction companies: *'[The national regulatory framework] must also provide [...] space for good local and regional solutions. [...] Create the legislative space for experiments, appropriate to the required pace and innovative strength. Experiments with new techniques financing constructions and (local) coalitions of (new) parties that can play a role in the combination of saving, demand and supply of energy are necessary to meet the challenges of the energy transition in the built environment.'* (VNG / NBN / BNL, 2017, pp. 2-3).

To conclude, it could be reasonably argued a shift in the dominant ways of thinking is ongoing and the socio-technical system is slowly changing towards a sustainable energy supply system (like described in **Chapter 2**). This is evidenced by increased exploration by the EU and the Dutch national government to create policies that offer space for innovations and the signing of agreements and intentions that are aimed to contribute to the achievement of their goals. However, as the respondents argued, care must be taken to ensure that an integral and customised approach with long-term goals is being maintained, and effective measures to really enable stakeholders and society to act are not sufficient (yet).

6.2.2 Identifying the current position of hydrogen energy applications in the energy transition in the built environment

Until recently, hydrogen energy applications for the built environment were not regarded to be a sustainable energy alternative that would be applicable on a large scale within the near future (Rijksoverheid, 2016b; TNO, 2017; Gigler & Weeda; 2018). During the *Klimaattafels* (consultation sessions) for the built environment in 2018 by the SER (2018), hydrogen was explicitly mentioned as a potentially suitable alternative for fulfilling heat demand in the built environment: *'Eventually, hydrogen could replace natural gas for the heat supply of houses and buildings'* (SER, 2018, p. 56). Interview respondents representing decentralised authorities acknowledge the increased attention that has been given to hydrogen energy applications for the built environment during the last two years (R4/R5; R7/R10): the project manager responsible for sustainable gas representing the province of Drenthe argued: *'During the last two years, hydrogen acquired a high position on the sustainability agenda'* (R7).

The potential of hydrogen energy applications for the built environment should be investigated by a broad coalition of stakeholders, while maintaining an explorative, reflexive and learning-by-doing-based approach (Gigler & Weeda, 2018; R2; R6). Societal support is mentioned to be crucial to increase the willingness of stakeholders to consider hydrogen energy applications, especially in a context like the built environment: *'Societal support for hydrogen [energy applications] is an important condition to successfully upscale hydrogen energy applications, particularly for applications that directly interfere in the daily lives of consumers or in situations where there is close interaction with hydrogen.'* (Gigler & Weeda, 2018, p. 63). More on this is to be found in Sections **6.3-6.5.**

The first tests with hydrogen-based energy for the built environment have taken place now and a growing amount of proposals for larger-scale pilots is now observed (R2; Gigler & Weeda, 2018). The most extensive pilot that has already been executed was the hydrogen – natural gas mixture pilot on Ameland between 2008 and 2012: *'On Ameland, [...] a test was held […] in which hydrogen was [...] mixed up to 20% by means of electrolysis in the existing natural gas network'* (TKI Gas, 2018, p. 40; Duurzaam Ameland, 2018). This pilot was an initiative of regional TSOs and the Ministry of I&W's predecessor and is seen as a success (R1; R2; R8). For an overview of all executed pilots that relate to the built environment, see chapters 3, 5 and 6 of *Overzicht Nederlandse Waterstofinitiatieven* by TKI Nieuw Gas (2018). These pilots have faced several smaller and larger barriers, mainly related to the uncertainty on affordable hydrogen availability and the legislative framework.

A break-through of hydrogen energy applications as a sustainable energy alternative for the built environment into the regime level of the energy transition in the built environment has not yet taken place; the necessary conditions to achieve this are not (yet) present in the socio-technical system (R2), which results in a lot of uncertainty among stakeholders regarding the feasibility of pilots: *'Pilots are a suitable means to gain experience with hydrogen. But then a lot of questions about safety issues and regulations arise'* (R6). More on the role of pilots as an opportunity to facilitate hydrogen energy applications can be found in Sections **6.3 - 6.5.**

The results above result in the conclusion that the facilitation of hydrogen energy applications for the built environment should be considered to be in a pre-development phase; awareness is growing and the options are actively being explored, but the socio-technical system has not yet adapted to be compatible with hydrogen energy applications. This causes reluctance among stakeholders to upscale ongoing pilots or to consider hydrogen energy applications as a feasible alternative for sustainable energy supply in the built environment.

6.3 Advantages of and barriers to hydrogen energy applications in the built environment

- This section presents the results to the sub-question: *What are the main opportunities and challenges for the facilitation of hydrogen energy applications in the energy supply system of the built environment in the Netherlands?*

As indicated in Sections **1.1** and **3.2,** the facilitation of hydrogen energy applications for the built environment is hypothesised to necessitate fundamental changes in the socio-technical regime. The document analysis and the semi-structured interviews resulted in a wide range of both opportunities and challenges related to hydrogen energy applications in the built environment. The following sub-sections categorise these different opportunities and challenges in five broad groups.

6.3.1 Attributes of hydrogen as an energy carrier

The first group of opportunities and challenges relate to attributes that are connected to hydrogen as an energy carrier. Next to the physical-technical potential of hydrogen for the energy supply system of the built environment (which have been outlined in **Chapter 2** and extensively discussed in Section **6.1**), the documents and respondents identified two important organisational-institutional barriers that relate to the characteristics of hydrogen in itself:

Categories of hydrogen
Although throughout this study, hydrogen energy applications are portrayed to be a sustainable energy alternative, it is important to remember that this is depends on the type of hydrogen that is used. *Contouren voor een Routekaart Waterstof* by Gigler & Weeda (2018) emphasises on the conditions in which the different 'colours' of hydrogen that are distinguished should be deployed (also see Section **2.3**). The initial incentive to consider hydrogen energy applications for the built environment is and has always been to increase sustainability.

Not all hydrogen energy applications are unconditionally sustainable in itself, however. That should not necessarily be seen as a barrier: *'Hydrogen [energy applications] need a certain scale level to eventually become successful. Grey, blue and green hydrogen could all help to accelerate the development of applications and to achieve economies of scale. Each of these three options is subject to different time perspectives, volumes and costs. Grey hydrogen could help to trigger the market for hydrogen applications, but the 'net direction of development' should be towards an increasingly small CO_2 footprint, and ultimately result in fully sustainable [green] hydrogen. This goal should be secured in the governance approach.'* (Gigler & Weeda, 2018, p. 4). This perspective is recognised by the interview respondents as well (R1; R2; R6): *'If other colours of hydrogen [than green] are going to be used, you should always think very carefully about the purposes […]. In my opinion, there are two reasons why you might want to do so. [The first one] is then about local emission problems […] in the urban environment. The second one is in case you intend to start a transition path towards green hydrogen. Obviously, the colour does not matter at all for the application in itself […] But for investors it is much more attractive to step in somewhere you already know that there is a certain market. On the basis of the existing, with a growth path to sustainability, then if you have to suddenly change of the system and tomorrow we switch to a completely new system that should be completely clean. So that growth path results in parties like Gasunie to find these developments really interesting.'* (R6).

Most respondents also acknowledge that at least blue hydrogen will actually be crucial in order to overcome challenges involved with the chicken-egg dilemma (see below), such as the development of equipment and investment costs in infrastructure (R0; R1). However, on the level of decentralised authorities and bottom-up organised projects, there seems to be a great desire to stick to sustainable (green) hydrogen. Their interest is mainly on sustainability goals and not so much on the development of hydrogen energy applications (Gemeente Hoogeveen, 2018a/b; R4/R5). This is also expected to be a challenge to the degree whether the case study will be successful, according to the representative of Gasunie: *'I am afraid that the project could fail due to desire to produce the hydrogen locally, which is in my opinion not the goal of the project'* (R8).

'Chicken or egg' dilemmas: availability and price of hydrogen
Academics, researchers and TSOs argue that large-scale implementation of hydrogen energy applications will mainly depend on the general availability of hydrogen. Hydrogen requires investments in the development and/or adaptation of energy infrastructures and appliances. These investments are not done as long as there is no stable demand for them. But the other way around is also true; when the appliances are not available and the infrastructure is not able to cope with hydrogen, no demand for hydrogen will be generated. These dilemmas are well recognised in the documents and by the respondents: *'If you look at hydrogen, and especially for the built environment, there is always a kind of chicken-egg dilemma that you are dealing with. The residents of the neighbourhood want cheap hydrogen. Well, how do you realise cheap hydrogen? If you have large-scale production. But when do you get large-scale production? If there is demand. But yes, that demand is not there yet.'* (R10). The representative of TenneT answered the ques-

tion *'What is according to you the biggest challenge to hydrogen energy applications?'* as follows: *'Scale size, and with it the price. These are the most important challenges for hydrogen in the energy transition and certainly also for the built environment.'* (R9). This cycle needs to be cut through in order to create more market potential for hydrogen energy applications for the built environment (R6; R0).

For green hydrogen, the feasibility of electrolysers seems to be a major uncertainty (R2; R9). They require large investments, and are thought not to be feasible if only used at times when electricity supply exceeds electricity demand (R6, R9). The effects of these plants on the grids are also not well studied yet (R8, R9): *'It is important that experiments be set up to gain more and better insight into the effects of [power-to-gas projects] on the energy infrastructure.'* (SER, 2013, p.89).

There is a high degree of uncertainty on how the development as an energy carrier will continue, according to R1: *'If there is […] more supply of blue and green hydrogen: it is difficult to predict what will happen then; chemistry will be able to use it, and mobility. If that starts to run, then it goes very quickly. And finally also the built environment: idem dito. The big problem that you will eventually get is, I think, that one will find out at a given moment: there is not enough renewable energy to produce all that green hydrogen.'* (R1). It seems that sector coupling, one of the great opportunities offered by hydrogen (see Section **6.1**), is emerging spontaneously when a critical demand has been reached (R6; respondent 7; Province of Drenthe). This is thus said to offer opportunities for hydrogen energy applications, but also is a threat because developments can go very quickly and negatively impact the affordability of hydrogen in that sense (R1).

6.3.2 A complex and uncertain future energy supply system

The second category of opportunities and challenges relates to the complexity and uncertainty that are argued to be present in the future energy supply system. The increasing number and interdependency of the relationships between energy sources, energy carriers, energy stakeholders, energy infrastructures and energy planners are argued to result in 'a fundamentally more complex and uncertain energy planning system', in which it is yet unclear which alternatives will be feasible and which will be not (R6; R9): *'[Therefore] I think that [the fact that every respondent so far had a different view on the role of hydrogen in the built environment] illustrates very well that nobody is knowing it yet.'* (R6).

Uncertainty about investment costs in infrastructures and appliances

As a niche development, hydrogen energy applications are subject to complexity, which is then resulting in uncertainty. All uncertainties result in high investment costs (Rijksoverheid, 2016b; Gigler & Weeda, 2018), which could be related to the chicken-egg dilemma outlined above in Section **6.3.1.** The types and scale levels of hydrogen applications that are considered are fundamental to this complexity: *'And then you still have the discussions on which scale level to apply the applications? Are we doing it on the level of a household? Or […] neighbourhood plants? […] the impact [of hydrogen energy applications on the existing infrastructure and its costs] is very much dependent on architectural choices regarding the grid. So, the closer you bring hydrogen to the home, the greater the impact will be. In order for you to know that the whole chain is right from the mains to the gas tap in your home. [...] Because then you have to go where you turn the hydrogen into heat and electricity, you have to start transporting it again. […] The further you go into the network, the more uncertain it is now'* (R6).

Complexity and uncertainty of the built environment

The complexity does not only depend on what options are being used on which scale level, but is also determined by the type of built environment that is concerned. *'Well, [investment costs are] really different for each situation. What the network operator, for example, does in that area, is also a lot of modelling. […]. I think that there is mainly the trick, that you can also make clear per neighbourhood what the consequences are if something becomes all-electric. Because then you can also see: yes, I have to increase cabling and cables, what I have to do with the connections, what should happen to the meters ... So there you have to sketch a certain picture and also have a clear understanding of what the impact is. Look if you really make everything all-electric, uh, then there* *would also be the key to what do you do for the rest? What do you do in the field of innovation? So you might be balancing locally, so you do not have to upgrade the grid.'* (R3). Due to this local context, municipalities are required to develop plans for each separate neighbourhood by 2021 and it is stressed by multiple interview respondents that this involves a customised approach *'[According to] the Environmental Act and Vision. And those municipalities have to think very carefully: what can I do a neighbourhood? Will I install a heating network? Or am I going to use green gas? Or maybe that hydrogen neighbourhood? […] You need to think about these kinds of issues. And every neighbourhood has its specific approach that depends entirely on what type of housing you have.'* (R10)

Infrastructure availability

One big opportunity that is identified in the documents and also by the interview respondents is the presence of a *'state-of-the-art gas grid'* (R3; R8) in the Netherlands, that is hypothesised to be suitable for the distribution of 100% hydrogen against relatively little investments: *'It is expected that large parts of the current natural gas system can be used for this purpose, which can reduce costs. It is also possible to build on a strong knowledge infrastructure built up in the field of natural gas.'* (SER, 2018, p.56). This opportunity is currently being further investigated: *'Netbeheer Nederland has commissioned KIWA for a study that maps out what is needed on the gas grid to adjust / upgrade to a fully sustainable gas network. The emphasis here is on hydrogen, but also will be looked at, among other things, biogas and green gas.'* (Gigler & Weeda, 2018, p. 42)

Therefore, the chair of HYDORGREENN argues that *'hydrogen energy will be ideal in some cases, especially because the infrastructure is already there. You just need to install another boiler.'* (R2). The social costs for adapting the existing natural gas grid to be suitable for hydrogen gas are expected to be acceptable, as respondent 1 points out while referring to the results of another study executed by Kiwa (a renowned testing and certification institute): *'the operational costs would increase by 5%-50%, which is considered socially acceptable'* (R1). According to the representative of RENDO, such '*an opportunity […] you cannot leave unused. You should at least seriously investigate it.'* (R3).

The availability of such assets creates local conditions that might be beneficial or less beneficial conditions for certain alternatives: *'You have to look a lot more at the national infrastructure, where is it smart to do something? That is why the hydrogen story here in the north of the Netherlands is so beautiful. Because part of it is based on the fact that we also have assets here. We have the Eemshaven, we have space, we have access to the gas networks, we have access to sustainable electricity, and we also have access to customers in the region. So it is a lot of conditions that come together and that are why it makes sense to do something here.'* (R6)

6.3.3 Involvement of stakeholders and society

Both the documents and the interview respondents repeatedly argued that involvement of stakeholders and society is a key element to the eventual implementation of hydrogen energy applications, if not the most important (SER, 2013; Rijksoverheid, 2016b). In the visionary document *Contouren voor een Routekaart Waterstof*, Gigler & Weeda (2018, p. 63) argue that *'Social support for hydrogen [energy applications] is an important condition to successfully upscale hydrogen energy applications, particularly for applications that directly interfere in the daily lives of consumers or in situations where there is close interaction with hydrogen.'*, which is a side note that is very much applicable to the built environment. For the successful implementation of the energy transition in the built environment, *'shared ownership is a condition. Everyone's contribution is needed. That is why citizens and businesses must be taken into account in all phases from planning to realisation.'* (SER, 2018, p.19) and *'awareness and social acceptance are the crucial factor for us as decentralised authorities to successfully act.'* (R10). In the case study project, these issues are a large part of the learning process and a separate work package is devoted to social acceptance (R2).

Sense of urgency

The sense of urgency for an energy transition that emerged in the Netherlands since recently, is argued to be an opportunity for hydrogen-based energy in the built environment: *'(…) That hydrogen at least* *more than now is going to be mixed in the gas grid in the future, I think that is clear for everyone. And there you also see that many TSOs are already making investments. [...] How far you can go, that is still a topic of discussion. That you say well: we're going to blend 20% or we're going to 100%? There are still many discussions about this. [...] But that it will find its place there? I think that is clear to everyone. I think the discussion about all-electric versus other solutions, and whether you think about heat networks, or alternative gases ... You know, that discussion has not yet been exhausted. And for now, let's say until not so long ago, all-electric was very much on the agenda. I think that, and certainly since Wiebes said: and now the gas tap will close in 10 years. Then it came even more prominently on the agenda as the alternative: electrification. Then the TSOs even put the bill on the table, right? That costs around € 50,000,000,000 in investments in the infrastructure. I think they were a little bit shocked after that.*' (R6). The decision made by the Minister of EZK in March 2018 was perceived as a strong albeit slightly unexpected incentive to consider alternatives for the built environment and to undertake action. However, the earthquake problems in the Northern Netherlands should be seen as a particularly local problem that stakeholders on an international scale level fail to identify with: '*Because we are dealing with the earthquake problem. That is actually very private, that is our problem here. While the rest of Europe says: well, gas is a solution in the transition.'* (R6).

Investment costs

'Property owners play a major role in the implementation [of the energy transition in the built environment].*They must actually invest in the sustainability of their premises.'* (VNG / NBN / BNL, 2017, p. 1) – costs are considered to be an important determinant of success for a sustainable energy alternative in an end-use sector where end-users usually limited resources. Therefore, the SER (SER, 2013; SER, 2018) argues that the affordability of alternatives should always be monitored, a vision which is shared by a large majority of the interview respondents: *'At the end, the end-user determines what solution he wants. But also what he wants to pay for it, and there is obviously a limited stretch in that.'* (respondent 6, New Energy Coalition). According to the representative of the municipality of Hoogeveen: *'I think, for the consumer, it is also: in part it is also hugely hyped. Hey, so everyone has to do things because, you have to cooperate, but if you look at it economically it often does not work out and that perspective is also very uncertain.'* (R4).

To reduce the challenges related to investment costs, financial incentives could be provided by competent, regulatory stakeholders (such as the EU, national government and decentralised authorities), which has been mentioned by all interview respondents. When reasoning about the future energy supply system, stakeholders tend to do so based on the current situation. However, it is pleaded for that a different approach could be applied: '*[...] If you say that [providing the heat demand] we want hydrogen, and you are going to use the same design principles, then it becomes quite unaffordable. While you might also say yes: [...] may not that heat supply be a little less unreliable? Because the costs for security of supply are also very high. And that is at odds with that sustainable energy supply. It could be an option to evaluate other financing models for energy supply in the future'* (R6). *'In the existing building stock, it is much more complex. If you want an all-electric energy supply there, it would be necessary to completely rebuild the outer shell […] before an electric heat pump could be efficiently used […] The power abilities you will need to meet your current levels of comfort in such situations are that much higher that […] three to four times heavier networks should be constructed.'* (R3).

Trust and experience

In the built environment, trust and experience are a prerequisite to gain support for hydrogen energy applications. But, according to the representative of Gasunie, *'Unknown makes unloved'* (R8). Currently, however, there is a strong focus on large-scale electrification in the built environment (R1; R6; R8; R9). That is argued to inhibit the development of other alternatives: *'But there [in the built environment] still dominates the wonderful story that electrification is unconditionally a good option, and that molecule-based energy carriers are unsustainable. That myth is still not punctured. So, it is in the minds of the people, who think electrification is sustainable and molecules are not.*' (R1).

A challenge is to be found in the fact that people tend to have negative associations with hydrogen, especially on safety, and interview respondents therefore argue that *'one of the biggest barriers to hydro-*

gen energy applications has to do with how to guarantee safety. [In] itself hydrogen ... is not an unsafe gas at all. It only has some properties that can make it unsafe. So you have to do something with that. And that means you have to have standards, that you have materials available, and that you need people who are allowed to do so.' (R6). However, it is also pointed out that hydrogen in the built environment is not new and that society could also get used to new technologies (R6; R9; R10). A representative of the Province of Drenthe illustrated this as follows: *'We have also regulated natural gas in such a way that people apparently find it very acceptable. While there are still deaths every year due to carbon monoxide poisoning. Very often through natural gas heaters. Yes, we are not even talking about that. That is actually impossible with hydrogen!'* (R10).

In order to solve such ignorance and worry, all interview respondents are convinced that conducting pilots and sharing the honest results of such pilots are the only way to enhance trust among society: *'I think the best way to convince society that hydrogen energy is not dangerous or scary, is to show it. Such as the hydrogen buses that now drive around in Groningen; such things show that technologies really work.'* (R6). As such, the sharing of successful pilots is a good way to stimulate and create awareness among stakeholders and society: *'Yes, share successes. Then it goes without saying: well, my neighbour has it, and I see that it works there, so I can do it too. And that's how I see it a bit with the hydrogen neighbourhood: it's a new neighbourhood, people see that it works, they probably also see (what I hope eventually comes out) that it is cost-wise also a very sensible choice. If you compare it with other variants. And that that is a very good incentive to say: well, yes, that's what I want to do, and I want to invest something because I see that it will eventually be okay.'* (R3). New energy technologies in the built environment are expected to be used at first by *'Pioneers […]. Among the residents, so people who are going to live there [in Nijstad-Oost/Erflanden] will make a deliberate choice to live in such an innovative development. To confirm it really works.'* Such an explorative, pioneering attitude among society could be used exploited by stakeholders *'to enhance follow-up projects and business cases'* (R7).

In the case of Nijstad-Oost/Erflanden, these are all strategies that are proposed to be used. The representatives of the municipality added that, for such innovative developments as Nijstad-Oost/Erflanden, it will be actively tried to market the project among *'people […] who are enthusiastic about pioneering. With a new energy solution.'* (R4). In order to enhance trust and experience, it has been proposed after a summer school held by the municipality in the summer of 2018 to *'build a kind of glass house with hydrogen energy applications, to literally visualise how things work and that they work safely.'* (R10). So far, people that live nearby the planned neighbourhood were not only suspicious, but also curious. After a consultation session on the new developments: *'What was very nice: also people from Erflanden, that neighbourhood that already exists next to it [were at that meeting]. And those people were there for two reasons: oh, if something happens next door, what about that safety? And, if it happens to them, then why not with us? We might want that too. The funny thing was: there were residents from the existing neighbourhood and security was an issue, but not very much. But, there were some worries, yes.'* (R6).

Stakeholder collaboration

Collaboration was mentioned by interview respondents as a great opportunity for sustainable energy alternative-related pilot projects, such as Nijstad-Oost/Erflanden in Hoogeveen: *'And the political managers are benevolent as well. Our representative is very enthusiastic about it and the alderman in Hoogeveen too. So they also know to find each other well. And that alone is a plus. That they also have the lights on green at the administrative level.'* (R10). The uncertainty causes reluctance to invest among stakeholders, but also enables stakeholders to explore the opportunities and challenges, as the representative of Gasunie argued: *'Yes, we want to step in now. Obviously, now it is definitely a small niche. But, it is also very unfamiliar to everybody. And if it turns out that it is very simple, hydrogen in the built environment, then it would be a shame not to use it. And we simply do not know all about that yet.'* (R8). A lack of stakeholder collaboration is seen as a challenge to move forward in the transition, by representatives of decentralised authorities: *'Groningen and Drenthe co-operate in the area of hydrogen. And it goes a bit with fits and starts, is my idea. So in my opinion, we as provincial authorities would be able to join forces with Groningen, so that cooperation can be achieved even more. And that less attention is paid to kingdoms. That there is not really an 'us' feeling, and not a 'we are the first',* *or 'we are the hydrogen province.*' (R10).

6.3.4 Legislative and regulatory framework

The fourth category of opportunities and challenges is to be found in the legislative and regulatory framework of the Netherlands. Although laws and regulations could be changed relatively easily by qualified authorities, the incompatible legislative framework currently prevents [regime level] stakeholders to explore hydrogen energy applications and to invest in hydrogen technology (R4; R7).

Deficiencies in the Dutch Gas Act

A first deficiency in the legislative framework is that according to the Dutch law on Gas (Dutch: Gaswet), hydrogen is not allowed to be distributed through the gas grid in quantities higher than 0,5% (Gigler & Weeda, 2018). The interview respondents touched upon this deficiency as well (R2; R8). This is considered to be a significant challenge to the implementation of hydrogen as an energy carrier: *''Well, the very annoying thing is that hydrogen gas is currently not a gas in terms of the Dutch Gas Act. Work can definitely be done there! […] If it were a gas according to the Gas Act, when that is all arranged. Then the customers also know what they are up to, and in my view it makes it easier for the market to use […] hydrogen as an energy carrier.'* (R8).

Safety regulations

There is a set of laws and regulations that is applicable to hydrogen, but these regulations currently have their basis in the industrial use of hydrogen rather than as an energy carrier that could also be used in the built environment: *'[If] you look at safety issues: there is neat policy on that. But that policy is aimed at industrial locations, and it includes, for example, safety zones of two kilometres. Yes, that makes no sense if you are going to apply it in a house. And that is also not necessary when you look at the volumes that are on a small scale.* (R6). There are no real rules on the use of hydrogen in the built environment yet (R2; R6). However, because hydrogen in the built environment is such a new development, a lack of rules also provides opportunities for experiments, as the representative of TenneT argued: *'A TSO [...] started a licensing process for the installation of an electrolyser in the built environment. And then you think: that will lead to a lot of problems. But if you just follow the license requirements, which are now there, it is much easier than e.g. an LPG installation. So that's really only when you finish the list, then you face far fewer obstacles (from the security perspective) to the construction and installation in the built environment [than you might expect].'* (R9). Such experiments are however executed in a lab setting. As soon as the lab setting is changed for a real setting, a lack of such regulations has consequences for the development of appliances: *'There are no combustion boilers that are suitable for hydrogen yet that are certified for use in the built environment. Therefore, no commercial tests could be done yet.'* (R2)

Tax regulations

Respondent 6 emphasises on the importance of tax regulations on hydrogen: '*And the taxes will be very important. On hydrogen ... It's not seen as gas now, so it's not fuel, so it is not part of the energy taxes. But, yes, that raises many questions. Also with investors. Does that remain so? If I convert my own power into my own hydrogen, and I sell that hydrogen ... Yes, normally you have to charge energy on that grid. But you now use it yourself as a means of production, and then it does not have to be. But do I have anything to do with that hydrogen? There are very many questions that relate to the tax regime. And you know one thing for sure: if we are all together, and suppose now that we stop using natural gas tomorrow, and natural gas is heavily taxed: of course it will not be the case that the government will say (which we are ourselves at the end): well, it is green, so we won't tax it.'* (R6). Such issues are complicated to solve, according the interview respondents connected to Gasunie and New Energy Coalition: *'And [although policy offers are thinking about these taxes], they will not be implemented within two years. That is just impossible.'* (R6). A suggestion that was provided was to expand the SDE+ regulations so that they also include conversion of electricity in sustainable gases. (R1) A lack of regulations results in stakeholders being reluctant to really explore and make investments in hydrogen technologies (R4).

6.3.5 Decentralisation of energy planning responsibilities

In the executed studies, it has been argued that *'in order to enhance local support' (*Rijksoverheid, 2016b, CE Delft, 2017; SER, 2018, p. 73*)* regional authorities '*[should] have a directing role in this. They provide a democratically legitimised local vision, can bring interested parties together and have good contacts with TSOs.'* (VNG / NBN / BNL, 2017, p. 2). As is acknowledged by the *Voorstel voor Hoofdlijnen van een Klimaatakkoord, 'Many proposals [...] will have consequences in town […], neighbourhood and home. How citizens deal with these consequences is partly determined by other issues that play at that level. [...] Participation [of regional authorities] is therefore of great importance [...].'* (SER, 2018, p.73). Therefore, decentralisation has taken place in the field of energy planning. Following from Section **3.3.5**, however, decentralisation is also expected to have inhibiting effects on the explorative abilities of decentralised authorities. Therefore, the respondents that are representing municipalities or provinces, as well as those closely working together with municipalities, have been asked whether they experienced a shortage of knowledge and resources regarding the governance of the energy transition in the built environment.

Provinces

The respondents connected to the Province of Drenthe did not experience major limitations to their role that are a consequence of decentralisation. Although *'[the project leader] always could use more people, we [the Province of Drenthe] do not experience a lack of human resources or knowledge in our role in this transition'* (R7). As the role of the province (further elaborated on in Section **6.4.2**) included the sharing of ideas and knowledge rather than the actual development of projects, the role of the province is also not very formal and therefore *'in depth knowledge about each specification of each technology is not required. That is present at the companies, like yours [Royal HaskoningDHV]'* (R7). The Province of Drenthe also helps municipalities who lack the knowledge and expertise to develop plans regarding energy transition by collaboration in multiple organisational structures, such as the *Drents Energie Loket* and the *Drents Energie- en Klimaat Overleg (DEKO)* (R10).

Although it was the province of Drenthe that first suggested the idea to use hydrogen energy applications, the case study project of Nijstad-Oost/Erflanden is a bottom-up developed initiative by HYDORGREENN, the Province and the Municipality (also Section **5.1**). On the field of hydrogen energy, the province has a Project Leader Sustainable Gas (R7) and about 25 other policy officers that work on sustainable energy available, according to respondents 7 and 10 (Province of Drenthe), who are willing to assist the municipality and HYDORGREENN but *'as long as they don't ask for us, we are watching the developments from the sideline.'* (R7).

However, in the general execution of the transition, a lack in terms of financial resources is experienced by the province: *'I think that the province can fulfil the [its] role perfectly, because I am afraid that if it is more coordinated from a national perspective ... [...] well, what we want, social support, that it will get jammed there. But I do think that the national government should make more resources available. This task is so great. And so much has to be done. And also to adjust the regulations accordingly.'* (R10)

Municipalities

In general, the respondents representing the municipality of Hoogeveen argued that the amount of discretionary competences regarding the energy transition in the built environment is sufficient and that they wouldn't want higher-order authorities to further interfere in terms of decision power, just like the Province of Drenthe argued (R4/R5). However, the Project Manager Sustainability argued that the amount of financial and human resources is not sufficient to integrate sustainability into all projects and policies: *'Looking at our organisation, in my opinion we are still too much organised in 'tubes.' […]. It is very much networking. In my opinion, Sustainability is all about networking. It is not so much about the technology anymore, about the substantive knowledge you have. I think. That is my role, also in relation to the province. And the neigh-*

bouring municipalities. It is a lot about connecting with them. 'I would like very much to integrate my portfolio with all other policy domains. But then there are limits to the capacity of the organisation. And the willingness, as well.' (R5).

With regard to the case study of Nijstad-Oost/Erflanden in Hoogeveen, the municipality did not experience a lack of human resources and knowledge, as *'these are mainly provided by HYDORGREENN'* (R5). The development of the residential area itself is quite a routine task for the municipality, which belongs to their normal tasks. The representative of RENDO (respondent 3) also explained that they help the municipality in optimizing such (and other) projects.

Regarding the energy transition in the built environment, the representative of the municipality experiences a lack in terms of capacity and financial resources, but also emphasises on the political will to truly act, which in his opinion might be more important than the actual availability of resources: *'Yes. And of course, what is always easier for us is if you have a driver who is very willing, who really is the figurehead and who really takes the initiative, and who says so to speak to us, what are you going slowly? That way you will not get it for each other. These are the interesting collaborations, so there is a vulnerable point. In every municipality. And, that [leadership] is certainly essential if you want to [solve problems] in a situation where the financial possibilities are very limited.'* (R4)

6.4 Dutch energy planning responsibilities for the built environment

- This section presents the results to the sub-question: *Which stakeholders are involved with the governance of the energy transition in the built environment in the Netherlands?*

In this section, the roles of each stakeholder that has been interviewed, as well reflects on the roles of the stakeholders that are mentioned in the analysed documents are being discussed. First, the stakeholders and their roles in relation to the case study are being discussed. Consequently, their roles in the wider context of the energy transition of the built environment are being discussed. For a discussion on which stakeholders are and which are not considered to be regime level stakeholders, see Section **7.1.4.**

6.4.1 Roles of stakeholders in Nijstad-Oost/Erflanden, Hoogeveen

There are three key stakeholders in the case study project of Nijstad-Oost/Erflanden in Hoogeveen, and two stakeholders that are important to the project but do not have a key role.

The final responsibility is with the Municipality of Hoogeveen. The project leader who is responsible for the planning process of the new residential neighbourhood is responsible for the contacts with other stakeholders involved in the project *'As project leader, I am responsible for the developments in Nijstad-Oost […] and the intention and ambition to use hydrogen for this [neighbourhood].* (R4) and also the one who wanted to experiment with sustainable energy alternatives in this neighbourhood. The Province of Drenthe brought in the idea to fulfil this desire with hydrogen energy applications, after meeting the coordinator of HYDROGREENN on a congress in Groningen: *'After that congress* (Wind Meets Gas, held in Groningen in September 2017), *the project manager of the province called me and said: There are plans to build a new neighbourhood, right? Some companies here are looking for pilots to experiment with hydrogen energy. Isn't that something for you?'* (Respondent 6, Municipality of Hoogeveen) For the energy part of this project, he is assisted by the municipalities' project leader on sustainability, who also is involved due to the district approach applied by the municipality of Hoogeveen (R5).

HYDORGREENN took responsibility for the development of the design of the hydrogen-based energy supply system of Nijstad-Oost/Erflanden: *'After several sessions, people from, I believe, 27 parties came to-*

gether and started brainstorming on the design of such a system. […] And then we realised a first concept plan.' (R2). The municipality and the other stakeholders regard the research institutes and companies that are part of HYDORGREENN as the main source of knowledge and expertise. HYDORGREENN itself is also the network in which all parties connected to the developments in Nijstad-Oost/Erflanden that are connected to hydrogen are united.

RENDO is the local TSO who is responsible for gas distribution in the area and, as such, has a significant role in the design of the infrastructure. Additionally, they have a responsibility in calculating the needs and limitations to hydrogen distribution in the existing neighbourhood of Erflanden. What is equally important, however, is the advisory role of N-TRA (RENDO's subsidiary branch which is responsible for anticipating on changes related the legal tasks of TSO that are involved with the energy transition). N-TRA argues that it offers reciprocal benefits to participate in this project: *'Well, I think our role is reciprocal. [...]. In the first place, as the local TSO, RENDO is responsible for the management and maintenance of the local gas grid […] and therefore, the admixing of hydrogen involves questions we want to get answered for ourselves, to get experience. What consequences does that have for pressures? Do we need to execute pilots and tests beforehand? […] We bring in a lot of expertise and experience on these topics. So yes, we see a clear role for ourselves there. And, at the other hand, in my role as an N-TRA representative, we are working together with the municipality on exploring the further opportunities of the area.'* (R3).

The Province of Drenthe acts as a facilitator and a bridging stakeholder in this development. Initially (before the municipality of Hoogeveen became a party associated with HYDORGREENN), the province of Drenthe brought them in contact with each other. The Province of Drenthe was the first stakeholder to propose the implementation of hydrogen energy applications in the new development in Hoogeveen, *'[The municipality of] Hoogeveen is clearly in the lead. We brought those two parties in contact with each other; we 'coupled' HYDORGREENN with the [municipality of] Hoogeveen. […]. Well, the municipality asked us for help there. But as long as they think everything is going as it should be, well then we take a step back as in our provincial role. Of course, questions will pop up at a certain moment […]. And then we are of course available to help. But, in the first place, the development of that neighbourhood is a municipal task.'* (R7).

New Energy Coalition is closely related to Nijstad-Oost/Erflanden as well, because it brings in a lot of knowledge and expertise, as well as a physical testing location for experiments (R2). New Energy Coalition is *'guiding one of the work packages, the ones that aims at integrating all available knowledge and thinking of issues related to social acceptance [of hydrogen energy applications], for example.'* (R6).

Many other stakeholders that are involved in some way with the developments in Nijstad-Oost/Erflanden were mentioned by the respondents. An overview of all mentioned stakeholders and their roles (if relevant for this study), as well as other formally involved stakeholders, is provided in **Appendix 7**.

6.4.2 Stakeholders and their roles regarding the facilitation of hydrogen energy applications for the built environment

EU

The EU has an increasingly dominant and steering role in energy planning, because *'an optimal energy mix, including the dynamic developments in the field of renewable energy sources, requires a continental market system at the very least. The energy market is the market sector that has the highest degree of efficiency potential in economic terms at a pan-European scale level'*, according to the European Commission (2010, p. 4) in their visionary document *Energy 2020*. The EU, however, only sets targets that should consequently be implemented on the national scale level by its member states (European Commission, 2010) and, as such, does not interfere with the competences of its member states in designing policies for the energy supply system on the built environment in how to achieve these goals (SER, 2013). In the facilitation of hydrogen energy applications, however, the EU could be a relevant stakeholder. The EU could provide opportunities for (substantial) subsidies to larger pilot projects in member states. R1 argues that some of the bigger market stakeholders are waiting for movements by the European Commission to perform more large-scale pilot projects. In addition, it is not expected that the Netherlands is able to solve the 'chicken or egg' dilemma connected to hydrogen energy (see Section **6.3.1**) on its own, and therefore it is argued that *'[an] approach based on an international scale level'* is necessary (R6) and that surrounding nations or the EU have a role in this part of the transition.

National government

According to the documents and interview respondents, the national government of the Netherlands has three important roles regarding the facilitation of hydrogen energy applications in the energy transition in the built environment: 1) long-term, unambiguous goal setting, 2) facilitation in terms of financing and 3) adaptation of legislative and regulatory frameworks. In general, the national government has the task to stimulate pilots in the field of hydrogen and to stimulate general action by stakeholders (Rijksoverheid, 2016b).

In the first place, the national government is seen as the main stakeholder to formulate consistent future goals and to provide financial resources, which consequently guide the actions of decentralised authorities and TSOs (R8; R9). Currently, *'Half-hearted choices are made, and way more financial resources are needed than those that are currently provided. […] I think that insufficient consideration is being given to funding opportunities for people who cannot afford it [the energy transition]. This can become a huge obstacle if a large part of the population turns to sustainable measures. And the people who are not able to come along will pay the bill later. That is unsalable. We have to take that into account.'* (R10).

Second, the national government also is in the lead of improving the subsidy systems to facilitate sustainable production methods of hydrogen. One method for doing so includes the extension of the SDE+ regulations, which should be adapted in such a way that conversion of renewable electricity into hydrogen is treated in the same way as renewable electricity, in terms of subsidy requirements (R1). This is currently not the case.

Third, the national government is responsible for adaptation of the legislative, regulatory and tax frameworks (see Section **6.3.4**). Implementing the necessary changes in the Gas Act to facilitate the transportation of hydrogen gas in the existing natural gas grid is one of such changes. The representative of Gasunie argues that the national government could also provide both an incentive to look for sustainable energy alternatives and show ambition by gradually implementing a progressive tax on emissions, as this would generate income for the government that could consequently be used to financially assist stakeholders with fewer resources to adapt their real estate property.

Provinces

According to the interview respondents, the role of the provinces in the energy transition in the built environment can be distinguished into 3 main functionalities: facilitation, coordination and, to a lesser extent, goal setting. The provinces are facilitating other stakeholders by both facilitation of interaction (connecting ideas) and providing financial assist to initiatives. There are no measures of pressure that could be applied by the province, but financial stimulation measures and facilitation of interaction are definitely helpful: *'[…] although we have no power to force parties to become more sustainable, we can bring parties together which might result in collaboration and new ideas'* (R7). A project manager involved in the Energy Expedition Drenthe Carbon Neutral 2040 summarises these roles strikingly: *[...] as a province, you could actually act as a facilitator, to bring parties together. Quite literally; we have meeting rooms available. [...] And we have financial measures: for example, the national government has a subsidy scheme for financing sustainability measurements on your home via loans, with a specific interest rate. Well, people in Drenthe* *pay a smaller interest rate as we compensate them further by ourselves.'* (R7) by whom knowledge and ideas are transferred to municipalities, niches and other provinces (R7/R10). Provinces have extensive competences as well to construct (financial) instruments that could stimulate stakeholders to act (R10).

The coordinative role of provinces is mainly by sharing and exchanging knowledge and experiences with municipalities, niche developments and other provinces. Examples are the development of the Regional Energy Strategies (RES), in which the provinces have an informal steering, supervising role (R10) and specific supra-municipal programmes that aim at knowledge sharing and overall coordination of policy. For example, all the municipalities in the province of Drenthe are part in the Energy Expedition mentioned above and this initiative is seen as very helpful for municipal policy makers: *'In that sense, I think it [the Expedition] is a very nice project. There are many opportunities for co-financing, a lot of goodwill to experiment with new initiatives...'* (R5). Provinces also monitor niche developments closely from the side-lines, such as the pilot in Hoogeveen: *'And [sharing] the knowledge as well. Because it is happening in Hoogeveen right now, the pilot with hydrogen energy applications. And imagine it will result in beneficial outcomes. Than we can expand this knowledge over the entire province. It is good then to be directly attached to the development.'* (R10). Provinces are also able to show stronger, more ambitious goals in the energy transition, as is mentioned by a provincial project manager*: 'And therein [the provincial policy programme] is actually stated [that the Province of Drenthe] wants to be carbon-neutral in 2040. We expressed a stronger ambition than the national government.'* (R7). They can also put the emphasis on certain elements to embed the transition more into the local context (R7/R10).

Hence, apart from providing financial and knowledge-related facilities, provinces seem to be crucial for a supra-municipal focus and coordination of different initiatives. What is particularly relevant for this study is that without this coordination, a learning-by-doing process would occur on a much smaller scale. Pilot projects are expected develop step by step, in a consecutive learning process.

Municipalities

In the energy transition in the built environment, municipalities tend to have more focus on the development and implementation of initiatives. Their role can be distinguished in two main functionalities:

First, municipalities are expected to design location-specific plans and policies: *'Decentralised authorities have a direct role in this. They provide a democratically legitimised local vision, can bring interested parties together and have good contacts with TSOs.'* (VNG / NBN / BNL, 2017, p. 2). For the energy transition in the built environment, each municipality must develop regional plans for each neighbourhood before the implementation of the new Environmental Law in 2021 (R5; R9; R10). Therefore, TSOs tend to see them as the *'main director of the energy transition in the built environment, at least.'* (R3), at least by other stakeholders. The municipalities themselves seem to be struggling sometimes to define their own roles, like explained by the Project Leader Sustainability of the Municipality of Hoogeveen: *It is quite difficult to find out what our role is. Because we have to facilitate, we have to sit on our hands, and we hear when they need us. [...] 'Facilitating', I get the hang of it! .A few weeks ago I spoke to a man [...] and he asked us: where is the municipality? Yes, I really enjoyed hearing that, because I asked him: may I interfere with it as well? Not that I want to take over, but this is just really nice.'* (R5).

Second, municipalities also have facilitating and coordinative functions, just like provinces but on a more local scale level. Municipalities can also design specific locally-fit financial stimulation measures and bring stakeholders together: *'We have a lot of financing constructions for this, we have advice, we have a very wide range of information and such, and so I think [...] we do that pretty well. [...] The home improvement loan, the stayers loan, the start-up loan, the sustainability loan, the ... Well, what else have we got? We've had the sun loan… […], so really the total package that you can find on the SVN page, that is available.'* (R5)

TSOs
Within the energy transition in the built environment, another important group of stakeholders consists of Transmission Network Operators (TSOs) (Rijksoverheid, 2016a, CE Delft, 2017). There are two types of TSOs in the Netherlands: national TSOs (Gasunie and TenneT; separated in terms of energy carriers) and regional TSOs (of which there are seven, which are responsible for regional grids of both natural gas and electricity). TSOs are responsible for the distribution of energy carriers from producers to consumers (CE Delft, 2017). The latter group is of particular interest for the built environment and the management of the energy transition in the built environment (R3; R8; R9). The role of TSOs in the energy transition in the built environment and the facilitation of hydrogen energy applications has two major components; facilitation and advice (R3).

The first element of facilitation is the traditional task that has been assigned to TSOs (*'[…] as a TSO, our main task is to facilitate [the orders from municipalities]'* (R3)). TSOs are responsible for the construction, management and maintenance of the grids for electricity and (natural) gas (R3; R8; R9). Due to this position the execution of the energy transition in the built environment, regional TSOs have a dominant role: *'[…], like all projects in the built environment: it is the regional TSO that is sitting in the front row'* (R8). All regional TSOs are connected to the national grids of Gasunie and TenneT, who until recently transmitted virtually all energy carriers onto these grids. Due to the spatially dispersed patterns of energy generation (also see Section **2.1**), this is changing however, which results in the situation that the interdependency between national TSOs and regional TSOs is increasing; *'Historically, it was the case (and actually still, to a large extent) that all energy carriers are being distributed by regional TSOs, are originating from national TSOs. And now, that is changing. Especially with electricity, but increasingly so for gas as well. […].The location where gas enters our grid is also subject to change. We already see that with the injection of green gas. The kind of gas could also change, in the sense that is no longer methane but hydrogen. That means the injection points are in different points and consequently that we need to adapt the infrastructure to the new situation. Especially in summer, this can lead to a lack of capacity in the regional grids'* (R8).

Because of the increasing complexity (also see **Chapter 2**, Section **3.3** and Section **6.3**), the advisory role of the TSO is increasingly important for decentralised authorities and other stakeholders in order to make decisions. TSOs have extensive knowledge of the energy supply system and knows best what the challenges are with regard to different sustainable energy alternatives (*'If you ask me, there [the regional TSO] lies the key to accelerate it. The municipalities will definitely need knowledge and ability to actually foster change.'* (R3), which is also acknowledged by the policy managers of the Municipality of Hoogeveen (R4/R5) and the Province of Drenthe (*'[…] They of course have all the technical knowledge on the grids'* (R7)) According to the interviewed respondents representing the TSOs, the extent to which the TSOs are involved might have severe impacts on the speed of the energy transition in the built environment: *'Yes, the role of the regional TSO… traditionally it is like 'we just facilitate', but I think that the TSOs should show their knowledge a bit more in this transition. Because the impact of the energy supply infrastructure… it can accelerate [the transition] enormously, but also slow it down.*' (R3) and *'[…] we have the knowledge of the electricity grid. And Gasunie has the knowledge on the gas grid. Together, we will be able to find ways for optimisation of these infrastructures.'* (R9). The Dutch TSOs work together in *Netbeheer Nederland*, and jointly conduct research and develop strategies to anticipate on the energy transition in the built environment. *Grid for the Future* by CE Delft (2017) was commissioned by *Netbeheer Nederland*.

Research institutes
According to the interview respondents, research institutes are also seen as important stakeholders. Research institutes are involved in both the technical and social so-called reflexive activities; hydrogen energy applications for the built environment are a new development that might involve serious consequences for the energy supply system, its infrastructures and its end-users. For example, research institutes like New Energy Coalition are the designated stakeholders to conduct experiments on how hydrogen energy will impact daily appliances like combustion boilers (R2; R6). These aspects have to

be adequately studied and this role is attributed to respectable, non-interest driven and neutral research institutes in order to enhance trust in society: *'Yes, I think that […] research institutes are the most suitable stakeholders to do that [conducting research on safety issues and sharing the conclusions with society]. These are quite neutral in conducting research and sharing the conclusions; on what are and what are not risks that are involved with hydrogen energy applications. And I also would say that people are more willing to accept these if you compare with what will happen if the municipality or the province will just say: 'but it actually is safe!'* (R10). In a certain way, this study contributes to the social-institutional side of the facilitation of hydrogen energy applications in the built environment.

Market

Finally, market stakeholders constitute an important group of stakeholders in the process of facilitation of hydrogen energy applications for the built environment; market stakeholders are the main developers of commercially suitable applications and for new applications to become market-ready. In the EU visionary document *Energy 2020* (2010) and in the *Energieagenda* by the Dutch ministry, market stakeholders are seen as *'crucial for the development of competitive new technologies, […] additionally contributing to the creation of jobs and welfare'* (SER, 2013, p. 5). In the *Energy Agreement for sustainable* growth, the SER also mentions that *'It is important that market parties conduct research into [...] applications of power-to-gas [...] and start concrete pilot projects to gain practical experience. In addition, research is needed for the application of hydrogen in the gas infrastructure (gas pipelines and storage) and in gas equipment, use of power-to-gas in industry [...] and in the production of heat'.* (SER, 2013. p. 89).

One challenge related to the role of the market, is that market stakeholders should see a perspective of (long-term) profit before they start investing in a new technology or application (R2; R7). In other words: there is nothing to facilitate by governments if market stakeholders do not develop new technologies. As such, the initial idea to experiment with hydrogen energy applications (regardless of location) was an idea from market stakeholders, also in the case of Nijstad-Oost/Erflanden (R6).

While municipalities are required to spatially implement pilots (R4/R5; R2), the technologies to conduct pilots with are commercially developed: *'And then we as market parties connected to HYDORGREENN said: we are willing to invest energy and time into it, to develop a new market. So in fact that is just a combination of ... We had a desire to test something and they wanted to develop a neighbourhood, and well, that is how these [HYDORGREENN and the Municipality of Hoogeveen] two parties actually came together. I think it is very strongly enabled because of that, because of course there suddenly is a lot of know-how'* (R2).

6.5 Monitoring sustainable innovative niches

- This section presents the results to the sub-question: *How are stakeholders responsible for the regime level of the energy transition in the built environment being influenced and changed by niche developments in the Netherlands?*

After the identification of stakeholders and their roles in the case study and in the general energy transition in the built environment in the Netherlands, the respondents have been asked how and in what conditions they deal with innovations in the energy transition in the built environment in general and with hydrogen energy applications in particular. Additionally, the document analysis provided useful points of references regarding this topic as well. Special attention is thereby given to the case study, but general remarks were given by the respondents as well.

6.5.1 Monitoring the niche of hydrogen energy applications

All interview respondents argued that they purposefully monitor niches in the energy supply system for the built environment. A first reason is that bottom-up organised initiatives for sustainable energy alternatives in the built environment are simply popping up and these have questions to the stakeholders the interview respondents represent (R3; R4/R5; R7/R10, R8). Additionally, the respondents expressed different 'internal' reasons to apply an explorative attitude as well.

The TSOs experience a strong incentive from ongoing developments regarding the challenges involved with the energy transition to actively explore the possibilities of hydrogen energy applications in the built environment. According to the representative of RENDO: *'For us, that [Grid for the Future (CE Delft, 2017)] was the trigger to decide to actively participate in the development of pilots [like Nijstad-Oost/Erflanden]. Additionally, What is also made clear from that, is that visualizing and conducting real pilots should now be central. We spoke enough about it; we want to translate those ideas into real applications!'* Therefore, they try to actively *'exploit the potential of hydrogen as an energy carrier [within the case study]'* (R3). The respondent representing Gasunie expressed similar motivations: *'For me that is a big question, how [fulfilling the energy demand of the built environment] will develop. [...]But we do want to prepare ourselves for hydrogen in the built environment. So that's why we participate in these kinds of studies ... Also to learn from it, but also to say that we as a society learn from all of this when you bring hydrogen into the built environment. […] That is a very useful process. You are now in the phase where you do not even know the questions. That is what we are doing now. And then, the next stage is to find an answer to those questions.'* (R8), just like TenneT: *'We are exploring hydrogen to map these [sustainable energy alternative] options, and to translate those into the possible challenges they have on our infrastructure. […] It is our task to manage our infrastructure'* (R9).

For decentralised authorities, it is a political goal to explore sustainable innovative niches, and a general acknowledgement that to achieve the goals connected to sustainability, action is needed: *'If you don't start because the task is too large, yes, then it doesn't work out at all. But if you say: okay, the task is enormous, and we need 15 years to do it but while applying a good strategy...? I think that is much more important.'* (R4). The same types of arguments were formulated by the representatives of the Province of Drenthe, while it was argued that participating in the pilot might result in well-applicable solutions: *'As a pilot, hydrogen in the built environment is very interesting indeed. It could be that answers arise to questions that you never thought about beforehand. And solutions that are very well applicable.'* (R10). To keep up with developments in this field, the province is aiming to be embedded in relevant networks: *'that is also why I am connected to HYDORGREENN. To follow developments in the field.'* (R10). In relation to the case study, the project leader Sustainability of the Municipality of Hoogeveen expressed a strong intrinsic motivation to develop new concepts and solutions in collaboration with other stakeholders to conduct the pilot: *'[Fulfilling the heat demand of Nijstad-Oost with hydrogen]: that's nice, that's nice, but it's in the neighbourhood behind it. You can also do those 88 homes all-electric, you know? That mass is big enough; you do not have to apply a difficult method like hydrogen. That is also possible, and then the TSO resolves it. But from the idea of: the development of new concepts, and that neighbourhood behind it. That makes the whole thing interesting!'* (R5)

This also touches upon another reason for such authorities to be involved in bottom-up developments and pilots, is to get exposure and publicity. This is seen as a side effect, but the representatives of the Municipality of Hoogeveen deliberately embraced the opportunity to use hydrogen applications for such reasons as well: *'And then, in the beginning of 2020, the first homes are being heated with hydrogen. Here, in Hoogeveen!'* (R4). So far, this seemed to have paid off, as quite a lot of attention has been given to the developments in Hoogeveen in the media (R5).

An additional reason to conduct such operational activities by monitoring niches is that most respondents believe that *'that bottom up approach in such developments [niches] is really a determinant of success for social acceptance.'* (R3); *'to maintain and manage the willingness of people, a bottom-up approach seems to really work well.'* (R10).

6.5.2 Facilitation of innovative niche developments

Just like the reasons for stakeholders to explore sustainable innovative niches, stakeholders also apply different methods and measures to do so. Most facilitative actions consist of financial assistance (subsidies) and knowledge-sharing. In the documents, these methods have also been proposed by the EU and stakeholders on the national level: '*More use should be made of more technology-specific support and financing instruments in line with the state aid rules when applicable'* (European Commission, 2010, p. 11) and similar recommendations are made to the National government of the Netherlands by the Socio-Economic Council (SER) that*: 'It is important that market parties conduct research into [...] applications of power-to-gas [...] and start concrete pilot projects to gain practical experience. In addition, research is needed for the application of hydrogen in the gas infrastructure (gas pipelines and storage) and in gas equipment, use of power-to-gas in industry [...] and in the production of heat'.* (SER, 2013. p. 89).

The representative of New Energy Coalition pleads for a radical, out-of-the-box approach that is fundamentally different from the current one: *'[It] is a liberal-economic policy, so they say: let the market decide. But the market needs clarity, and not: just do something innovative. The market just wants to know where they stand, and I think that requires more control from the government. In the field of regulation, in the field of taxation, in the field of subsidies, but also firmness in it. And now, what you actually see is that we actually have innovation-driven subsidies. Hey, so let's see? Well, that is possible, then the subsidy goes off immediately and then we move on to the next innovation. Yes, that does not mean that these innovations will land.'* (R6)

To be better able to do so, the representative of RENDO argues that more policy space should be provided to the local TSO: '*In that you see that complexity results in the need for more locally-tailored solutions. Due to the extensive knowledge on infrastructure, this is essentially a task of the regional TSO […]. They [TSOs] have that overview, and I think it is most important for us to be able to play a role in this. We are now very tightly regulated, but how much more can we think and participate in this? Well, those experimental spaces are also important. And I think it is also very important that you give clarity on specific matters from a government policy at a certain point in time. [...] That regulation that you deregister as a government is then of course… it can have a great deal of influence on the developments of such technologies. So it's good to think about that very much. With many market parties to seek consultations of well, what is the convenient way?'* (R3). Gasunie and TenneT (the national TSOs) have similar arguments:

A challenge related to such processes is *'that policy always lags behind the initiatives. […] But you see something coming up, and you think that with all good intentions you give a kind of policy and support. And if that that does not have the desired effect, that is of course very sad.'* (R7). It is pointed out that *'national policy is always somewhat lagging behind'* (R6). Therefore, the representative of the TSOs argues that *'Since it is really all still in the initial stages, a learning process, […] I think that within the municipality you also have to start working on a kind of knowledge and expertise centre. In which the TSO(s) and […] social organisations that can work together in this. So that you, yes, get a support base and a playing field as wide as possible. But ultimately the focus should be on actually doing things.'* (R3)

For the municipalities and provinces, sustainable innovative niche is undertaken by the appointment of special officials who are in charge with sustainability affairs. Within the case study project, the project leader of the new neighbourhood works together intensively with the Project Manager Sustainability (R4/R5). In the Province of Drenthe, the developments are being monitored by a team of about 25 people, of which one is specifically responsible for everything that relates to sustainable gases (R7/R10).
For stakeholder collaboration (see Section **6.3**), formalised agreements are argued to be necessary (R4). These formalised agreements create clarity, but also pone barriers; HYDORGREENN experiences barriers in their desires to execute pilots as there tend to be many requirements to be eligible to subsidies due to such formal procedures: *'And instead of being busy all the time to satisfy all sorts of officials to fill in some excel list that they created, again … [we prefer to actually do and develop things].'* (R2). He also stresses that in order for a take-off, *'[we] just need money to do pilots, to put it simple.*' (R2). These are also recognised by the decentralised authorities: *'There is simply a lack of direction, lack of clarity, very much is still driven by financial interests, for a very large part. So that transparency and that relaxation, that's important, but*

that you have to look at it properly ... Yes, I think that's missing a bit.' (R4). It appears, however, that in relation to the case study there are sometimes conflicting interests regarding the facilitation of sustainable innovative niches: *'When we started talking to HYDORGREENN, HYDORGREENN told me of what do you really want, as a municipality? What should we do? I say: well, I do not think that works like that, because I think you have a clear interest: they think the hydrogen economy is going to be very big, and they are looking for pilots to get that out and finally put money into it, to earn. And I say: I think the question is: what is your idea! And finally we need to provide that common, and I say I do not feel like [only] to talk, I want to actually do it.'* (R4).

What is particularly interesting for hydrogen energy applications in relation to facilitation by stakeholders, is that governments could break through the chicken-egg dilemma (outlined in Section **6.3.1**) by acting as *'a launching customer'* (R7). Governments, both the national government and decentralised authorities, *'could create demand by being the first stakeholder to invest in a basic infrastructure and conducting the first experiments. This is the approach that Groningen is hesitatingly starting to use nowadays'* (R6). A prerequisite for such an approach is having an active and explorative attitude, because acting as client involves adhering to EU procurement regulations, *'and tenders usually are based on, and that is also a bit of laziness, proven technology.'* (R6).

To conclude, respondents touched upon four different approaches for stakeholders to facilitate sustainable innovative niches: 1) provide subsidies or other means of financial assistance, 2) creating space for pilots by taking away legislative and regulatory barriers, 3) applying an explorative attitude towards such developments by participating in relevant networks and 4) acting as a launching customer

6.5.3 The emergence and ambitions of HYDORGREENN and Nijstad-Oost/Erflanden as a niche development

In order to get a better understanding of how the niche development in Hoogeveen actually started, it is relevant to have some background information on HYDORGREENNN. Therefore, the chair of HYDORGREENN was asked how HYDORGREENN emerged and how they started thinking of hydrogen energy applications for the built environment: *'How HYDORGREENN was established? Everyone is talking about hydrogen. Hydrogen projects, hydrogen ... But actually few projects really came off. So then actually Stork and EnTranCe, some guys who already knew each other [...], said: Can we not just get all the important people [who have something with hydrogen] together and just explore how we can execute pilots? That is where the little boat came into existence: we thought very simply of who are the top 20 of industry and politics and business that could or would like to do something with hydrogen. Bring them together on one boat ... And now there are more than 80 companies and organisations affiliated with HYDORGREENN.'* (R2). It resulted in the emergence of a broad coalition with stakeholders from different backgrounds. It functions as an open innovation platform, in which stakeholders aim to build up knowledge, experience and trust, while at the same time experiment with pilots. Regarding the built environment, in such a session the idea popped up to start an experiment with a hydrogen-based village: *'Then the idea popped up: Let's experiment with a village on hydrogen. Just an idea. Now that we have discussed, what is connected with such a plan?'* (R2)

The chair of HYDORGREENN argued that this is a big strength of HYDORGREENN: *'Actually, we have the entire chain represented in HYDORGREENN. I mean: we have the big parties, like NAM and Gasunie… All the way down to the boiler developers, to just mention an example. […]. That is a big plus.'* (R2). However, the representative of New Energy Coalition (the organisation into which EnTranCe merged in early 2018), also argued that such a broad group of stakeholders could eventually result in a lock-in: a lack of shared vision and progress: *'And that [such a big coalition] is not easy, because that means you start with a lot of people. Anyone who wants to, can join. If you are not careful you will repeat the discussion every time because there are new people, and at the same time you try to build up a bit of knowledge with each other.'* (R6).

As an open innovation platform, HYDORGREENN has a clear vision that if the pilots in Nijstad-Oost/Erflanden are going to be successful, these should result in commercial upscaling: *'Nijstad-Oost functions as a vehicle for us to test all these things. Because then you have a real environment, you have real people, you have a real residential area. It is not a paper exercise; it is really planned and we are really going to build this. So that is just different than when you say yes, we are going to look at what we could all go against if we would do this. No, we just have real citizens, we have concrete architecture, we have real pipes in the ground. We just have to do that with you and in one way or another we find that in every VINEX neighbourhood in the Netherlands. So when we have finished, we can say to all those other municipalities: you can just all do this.'* (R2). However, because of the different roles of the involved stakeholders they have a different list of priorities and expectations as well regarding the case study. For research institutes, *'[It] could be a satisfactory outcome that the whole project will not continue. Because you also learned something with that; we do have a good proposal, and we have clearly mapped out where the issues lie, but we have also learned that the time is not ripe yet. People have no money to finance it yet. Is that actually a problem? Others have different interests and will continue anyway.'* (R6). For other stakeholders, that is a missed opportunity to build up necessary knowledge on how hydrogen energy applications function in reality, close to the end-user (R8) or to lose the opportunity of positive publicity and exposure (R4/R5). Appliance developers (for a list of involved technology-related companies, see **Appendix 7**) miss out the opportunity to get some of their R&D costs refunded as subsidies (R6).

6.6 Opportunities and challenges in the governance of the Dutch energy transition in the built environment at the regime level

- This section presents the results to the sub-question: *Which opportunities and challenges are present in the governance of the energy transition in the built environment in the Netherlands to foster facilitation of hydrogen energy applications at the regime level?*

The sections above illustrate the Dutch energy planning system for the built environment from a transition perspective and the position of hydrogen energy applications and their opportunities and challenges therein. These results provide an extensive framework of reference for identifying opportunities and challenges in the governance of the energy transition in the built environment that could foster the facilitation of hydrogen energy applications for the built environment. Following Section **4.6**, these findings are structured in a SWOT analysis. By identifying and categorising the statements of the respondents as strengths, weaknesses, opportunities and threats in AtlasTI, an overview of these elements is generated. The results of this SWOT analysis are visualised in the SWOT matrix that is presented below, in Table **6.1.**

*Table **6.1:** SWOT matrix for facilitation of hydrogen energy applications in the governance structure of the energy transition in the built environment in the Netherlands.*

	SWOT matrix	
	Helpful for facilitation	***Harmful for facilitation***
Internal factors	**Strengths**	**Weaknesses**
	▪ Recent growth in awareness of the wide applicability of H_2 among stakeholders	▪ Lack of shared perspective among stakeholders on the position of H_2 in the energy transition in the built environment
	▪ Shared perspective on key role of hydrogen in future energy supply system	▪ Lack of integral and cross-sectoral approach in policy making on energy transition in the built environment
	▪ Presence of willing and collaborative stakeholders (e.g. HYDROGREENN)	▪ Lack of knowledge, experience and trust among stakeholders and society
	▪ Willingness of legislative authorities to provide legislative space for experiments with H_2 in the built environment	▪ Lack of regulations and incompatibility of laws on the use of H_2 in the built environment
	• Wide discretionary competences of decentralised authorities for creating own focus in the transition	▪ Lack of shared ambitions among stakeholders ▪ Dual roles of stakeholders in initiatives and regime
External factors	**Opportunities**	**Threats**
	▪ Shared high level of awareness and sense of urgency on the need for change in the socio-technical system among stakeholders	▪ Chicken-egg dilemma and associated investment costs issues
	▪ Availability of important assets in the Netherlands (existing natural gas network, renewable electricity potential)	▪ Uncertainty on general availability and price of hydrogen
	• Potential for sector coupling	▪ Highly dynamic and volatile institutional context in the Netherlands: lack of directive visions of the national government
	▪ A lot of initiatives for pilots are emerging in the Netherlands	▪ Perceived safety issues may inhibit social acceptance
	▪ Wide discretionary competences of decentralised authorities for creating own focus in the transition	▪ Lack of shared perspective on the energy transition in the built environment in international context; the Netherlands is unable to solve the chicken-egg dilemma alone

6.6.1 Strengths

The **strengths** visualised in the SWOT matrix are elements present in the governance of the energy transition in the built environment in the Netherlands that internally relate to hydrogen energy applications and which are considered to be beneficiary for the facilitation of hydrogen energy applications in the built environment in the Netherlands.

Awareness of the wide applicability of hydrogen as an energy carrier

An important strength that is present in the governance structures of the Dutch energy transition in the built environment is the shared awareness of the wide applicability of hydrogen as an energy carrier. It results in a situation in which stakeholders are willing to explore the opportunities for hydrogen energy applications in the built environment (R1; R2; R4/R5; R6; R7; R8; R9).

Shared perspective on the key role of hydrogen in the future energy supply system
Additionally, there is a shared perspective among stakeholders that hydrogen will have a key role in the future energy supply system. Such a perspective enables stakeholders to look for opportunities to use hydrogen in all end-use sectors of the energy supply system (R1; R3; R8; R9).

Presence of willing and collaborative stakeholders
Both market stakeholders and (semi)governmental institutes are willing to facilitate and experiment with hydrogen energy applications, and they are collaborating to do so (R2; R3, R4/R5; R7/R10; R8; R9).

Willingness of legislative authorities for institutional change
The legislative authorities apply a willing attitude to adapt the institutional framework in order to facilitate hydrogen energy applications in the built environment, and as such create room for pilots and, possibly, upscaling (R2; R3; R7; R9).

6.6.2 Weaknesses

The **weaknesses** visualised in the SWOT matrix are elements present in the governance of the energy transition in the built environment in the Netherlands that internally relate to hydrogen energy applications and which are considered to be obstructive to the facilitation of hydrogen energy applications in the built environment in the Netherlands.

Lack of shared perspective among stakeholders on the position of hydrogen in the built environment
There is currently a general lack of shared perspective among stakeholders on which position hydrogen energy applications will have in the energy supply system of the built environment. This is argued to slow down pilots as stakeholders do not agree on which applications are going to be successful and in which situations. This is mainly a consequence of the uncertainty on the energy transition in the built environment, which results in complexity (R1; R4/R5; R8; R9; R7/R10).

Lack of integral, cross-sectoral approach in policy on the energy transition in the built environment1
Although many visionary documents and policies aim at establishing an integral, cross-sectoral approach in the energy transition in the built environment, not all stakeholders seem to experience such an approach in reality. As for hydrogen sector-coupling and wide applicability are key attributes that offer opportunities, a lack of such an approach could result in a slow-down of the facilitation process (R2; R9; R10).

Lack of knowledge, experience and trust on hydrogen energy applications
Stakeholders and society alike have a general lack of knowledge, experience and trust with regard to hydrogen energy applications in the built environment, which limits their willingness to facilitate them (R1; R2; R8; R9)

Lack of regulations and incompatibility of laws on the use of hydrogen in the built environment
Stakeholders are hesitating to facilitate hydrogen energy applications for the built environment because there is a lack of regulations regarding hydrogen use in the built environment, and there are major deficiencies in the law that inhibit the transportation and production of adequate supplies of hydrogen (R2; R6; R7; R8).

Lack of shared ambitions among stakeholders

Many stakeholders have different ambitions and interests regarding hydrogen energy applications in the built environment, next to the shared perspective that hydrogen will be a key component in the energy transition and that hydrogen is a suitable energy carrier for the built environment. A lack of shared ambitions and interests might result in the failure of pilots, which inhibits the facilitation of hydrogen energy applications in the built environment. The case study illustrates this quite well: market stakeholders see it is a project to get subsidies for something they will execute anyway (R2; R4), while research institutes and TSOs see it more as a learning process, where knowledge acquirement has a big role (R3; R6; R8).

Dual role of stakeholders
Stakeholders who are involved in the pilots tend to have dual roles; at the one hand they have the task to exploit the current system and to facilitate the desires of democratically taken decisions, while at the other hand they try to anticipate on niche developments and to gain knowledge. This is especially the case for TSOs (R3; R4/R5; R6; R7/R10).

6.6.3 Opportunities

The **opportunities** visualised in the SWOT matrix are considered to be beneficiary for the facilitation of hydrogen energy applications in the built environment in the Netherlands, but these are present in the wider context of the energy transition in the built environment and do not necessarily apply to hydrogen energy applications specifically

Shared sense of urgency on the energy transition in the built environment
Especially since the decision by the Ministry of EZK to abolish gas extraction in Groningen, a shared sense of urgency to shift away from the current energy supply system based on fossil fuels towards a different system emerged. Such momentum results in stakeholders becoming more explorative towards sustainable energy alternatives such as hydrogen energy (R2; R5; R8; R9)

Availability of important assets that are suitable for hydrogen
Another big opportunity is to be found in the existing natural gas grid and the planned potential of renewable electricity, which exceeds the current demand for electricity. These provide both the need and the possibility to increase hydrogen supplies, which result in lower prices and higher demands (R1; R2; R3; R6; R8; R9).

Potential for sector coupling
In order to solve the chicken-egg dilemma, the possibilities of hydrogen for sector coupling might result in the situation that stakeholders are more willing to facilitate the use of hydrogen energy applications in the built environment (R1; R7; R8; R9).

Growth in the amount of initiatives and pilots
An increase in the amount of pilots and initiatives to experiment with hydrogen energy applications in the built environment is currently being observed in the Netherlands (R2; R3; R6; R0)

Extensive competences for decentralised authorities to apply own focus in the transition
Although this could also be classified as a threat, the current institutional organisation of the energy transition in the built environment leaves extensive competences for decentralised authorities to embed an own focus in their approach. In the case hydrogen energy applications fit within this own focus, it could result in an acceleration of the facilitation process (R3; R4/R5; R7/R10).

6.6.4 Threats

Threats are also considered to be obstructive to the facilitation of hydrogen energy applications in the built environment in the Netherlands, but these are present in the wider context of the energy transition in the built environment and do not necessarily apply to hydrogen energy applications and/or the built environment specifically.

Chicken-egg dilemma and associated investment cost issues
As long as there is neither a stable hydrogen demand nor a stable hydrogen supply, a strong chicken-egg dilemma effect is to be expected to slow down the facilitation and implementation in the built environment, because prices will be too high to be feasible in the built environment (R1; R7). This cycle needs to be cut through in order to successfully upscale (R6; R0).

Uncertainty on the general availability of affordable and sustainable hydrogen
Although there is a shared perspective that hydrogen will have a key role in the future energy supply system, there is a lot of uncertainty on when and how this will exactly materialise, and what 'colour' of hydrogen will be available at what price. This has consequences on the extent and speed of the implementation of hydrogen energy applications in the built environment (R1; R7/R10; R9).

Dynamic and volatile institutional context
A well-organised energy transition benefits from a stable institutional context. Such a context is currently lacking; dynamic developments in the field of the energy transition result in the situation that a long-term ambition is lacking and that responsibilities tend to shift from one stakeholder to another quite quickly. Such a volatile context results in uncertainty and reluctance among stakeholders to explore alternatives. Market stakeholders and decentralised authorities experience a lack of clarity (R2; R5; R6; R10)

Perceived safety risks
Social acceptance of hydrogen energy applications might be obstructed by perceived safety risks of hydrogen (R6). Honest and objective answers should become available and being communicated by respectable stakeholders to tackle such a risk (R4/R5; R10).

Lack of shared ambition and vision on the energy transition in an international context
The Netherlands are probably not able to entirely solve the chicken-egg dilemma on its own and therefore a shared vision or strategy in collaboration with other countries should be established. Those countries tend to have different focuses on the position of hydrogen however; they see natural gas as an option which for the Netherlands is not really an option due the earthquake problems (R1; R6)

6.7 Main findings

The main findings from the document analysis and the semi-structured interviews per sub-question are summarised below:

- **Hydrogen** as an energy carrier is seen as a key element in the future energy supply stem, although stakeholders have widely different views on its **potential in the built environment**;
- The **energy transition in the built environment** is currently argued to be in a **take-off phase**, while the current level of **facilitation of hydrogen energy applications** therein fits most with the **pre-development phase;**
- The main **opportunities** for the facilitation of hydrogen energy applications are 1) the availability of suitable infrastructure 2) a large potential for sector coupling, and 3) a willing and collaborative attitude of stakeholders towards hydrogen in the built environment The main **challenges** are 1) a lack of integral vision at the national and European level on the energy transition in the built environment, 2) complexity (which results in uncertainty) on the availability of sustainable and affordable hydrogen and the feasibility of the in different types of the built environment and 3) involving society.
- With regard to the **roles of stakeholders**, the provinces and regional TSOs are expected to have a key role in bringing hydrogen energy applications from the niche to the regime level. The provinces have a strong facilitating and coordinative role, as they support municipalities and market stakeholders to conduct stakeholders; they can give hydrogen energy applications a certain profile. The role of the regional TSOs is important because they have extensive knowledge on the infrastructures and are most capable of executing cost-benefit analyses on the potential of hydrogen energy applications.
- Facilitation and monitoring of **sustainable innovative niches** is done at all levels and by all stakeholders, by applying an explorative attitude and participating in learning processes.
- In the **governance** of the energy transition in the built environment, hydrogen energy applications could be fostered by regime level stakeholders by providing financial assistance, acting as a launching customer and providing legislative space for pilots.

7 Discussion, conclusion and policy recommendations

In this chapter, the results are being critically discussed in relation to the theoretical framework (**Chapters 2 & 3)** in order to discuss whether the research objectives drawn up in Section **1.1** have been met. Consequently, answers are formulated to the connected research questions (Section **1.2**)**.** Last, the main research question is answered (Section **7.2**) and policy recommendations are provided (Section **7.3**).

7.1 Sub-questions

7.1.1 Potential position of hydrogen energy applications in the energy transition in the built environment in the Netherlands

The first sub-question of this study aims at identifying the potential position of hydrogen energy applications within the context of the energy transition in the built environment. **Chapter 2** provides an extensive description of the challenges of the energy transition in the built environment, the characteristics of hydrogen as an energy carrier and the opportunities it offers to cope with the technical challenges of the energy transition in the built environment. This section discusses whether these are recognised by stakeholders and what consequences these will have for the position of hydrogen according to them.

Discussion: Position of hydrogen in the future energy supply system
Because of the characteristics of hydrogen as an energy carrier as formulated by Armaroli & Balzani (2006), Verfondern & Teodorczyk (2007) and Ball & Wietschel (2009) (amongst others), hydrogen is seen as a key component of a sustainable future energy supply system (CE Delft, 2017; R3; R9). It appeared that this key position could be attributed to the abilities of hydrogen as an energy storage mechanism (as described by Anderson & Leach, 2004) to cope with the intermittency problem that is involved with the energy transition (*'it is a bit like the holy grail in the energy transition'* – R6), but the other opportunities of hydrogen (sector coupling (e.g. Agnolucci & McDowall, 2007; Guille & Cross, 2009) and the advantages of hydrogen to be easily transported, stored and traded (Dodds et al., 2015; Fekete et al., 2015) are equally important to different respondents. The easiness of storage, for example, is seen as crucial by R1 (University of Groningen) and R9 (TenneT) and sector coupling is argued to be a key opportunity in *Contouren voor een Routekaart Waterstof* and also in the *Voorstel voor Hoofdlijnen van een Klimaatakkoord* and most of the interview respondents.

Although these characteristics are all widely acknowledged and each document and respondent argued that hydrogen will become more important in the future energy supply system, it was mentioned in *Grid for the Future* (CE Delft, 2017) and by various interview respondents (R6; R8; R9) that the exact position of hydrogen as an energy carrier will be dependent on crucial societal and political choices that are going to be made in the next years.

In the theoretical framework, not so much attention has been given to the integral role of hydrogen in the wider energy supply system; instead the focus was on the position of hydrogen in the built environment. However, both the documents and the interview respondents pointed out that the position of hydrogen in the built environment is completely dependent on the degree to which hydrogen will become part of the wider energy supply system.

Discussion: Position of hydrogen energy applications in the built environment
The challenges of the energy transition in the built environment, which include the demand patterns described by Van Kann (2015), the intermittency problem (Clastres, 2011; Smale et al., 2017) and the need for systems integration (Clastres, 2011) were widely confirmed in the analysis. That is also true for the possibilities of hydrogen energy can offer to cope with these challenges in this energy end-use sector (as described by e.g. Dodds et al., 2015 (heating); Edwards et al., 2008 (electricity) and Anderson & Leach, 2004 (energy storage). The interview respondents and documents, however, almost exclusively treated hydrogen energy applications as a means to fulfil heat demand on the scale level of the built environment (Gigler & Weeda, 2018; SER, 2018; R8). Only HYDROGREENN (R) and one of the project leaders of the Province of Drenthe (respondent 10) touched upon experiments with hydrogen to do energy storage on the level of a single building with hydrogen. RENDO (R3), Gasunie (R8) and TenneT (R9) responded that other options on the rather small scale level of a single building are usually more efficient and especially less expensive. On the neighbourhood level, such applications however could be 'interesting suggestions for research' (R3; R6; R9).

The exact position of hydrogen energy applications in the built environment will, as mentioned before, be dependent on the exact position of hydrogen in the wider future energy supply system (CE Delft, 2017) as well as on the feasibility of alternatives (R6; Ball & Weeda, 2015) and is therefore hard to predict (R1), regarding the focus of this study on the built environment. In the interviews, two schools of thinking were discovered: 1) situations with end-users that have high energy consumption levels and 2) situations where large-scale electrification and heating networks are not feasible because of financial and/or aesthetical reasons (also see Section **6.1.2**).

Answer to sub-question 1

- *What is the potential role of hydrogen energy applications in the future energy supply system for the built environment in the Netherlands?*

It can be concluded that, due to the fact that hydrogen is seen as a key element in the Dutch energy transition (which is a context that is prone to an increasing amount of complex interdependencies which result in a high degree of uncertainty, see Section **7.1.3**), hydrogen energy applications in the built environment could be reasonably expected to be at least be considered as a suitable sustainable energy alternative to fulfil heat demand in situations where either alternatives are not a feasible option due to financial or aesthetical reasons, or in situations where buildings have high energy consumptions and that are easy to adapt.

7.1.2 Current position of hydrogen energy applications in the energy transition in the built environment

Following transition theory (e.g. Rotmans, 2010; Geels, 2011), in order for a transition to reach its take-off phase, the speed of change should be increasing at a higher rate than before (Rotmans et al., 2001). However, it does not provide tangible indicators to objectify such a higher rate of change. Therefore this study aims at identifying the current phase of the energy transition in the built environment in the Netherlands is in general and with regard to hydrogen energy applications.

Discussion: theoretical similarities between diffusion of innovations and transition theory
Both in the theoretical and in the empirical part of this study, interesting similarities have been identified between the diffusion of innovations approach as applied by Rogers (2010) and transition theory (e.g. Rotmans et al., 2001; Van der Brugge, et al., 2005; Loorbach, 2007). The five respectively four phases fit well into each other and are also perceived in the same way by interview stakeholders; the market

readiness of various hydrogen applications reflects the extent to which they are already facilitated and incorporated into the regime. For example, the admixture of hydrogen into the natural gas grid is already experimented with on a larger scale and since a longer period of time as the investment costs and uncertainty are much lower (R2; R6). In other words, they are more market ready (early adopters phase by Rogers) and starting to reach the start of take-off phase (by Loorbach) than 100% hydrogen combustion or stationary fuel cell technology (see Section **2.2**). These findings provide interesting points of reference for decision makers to indicate if a certain technology is suitable for upscaling in the transition; such technologies are argued to meet the four prerequisites (Geels & Schot, 2008 (in Section **3.1.2**) in order to be able to reach the second phase. Figure **7.1** shows a conceptual comparison of these two approaches.

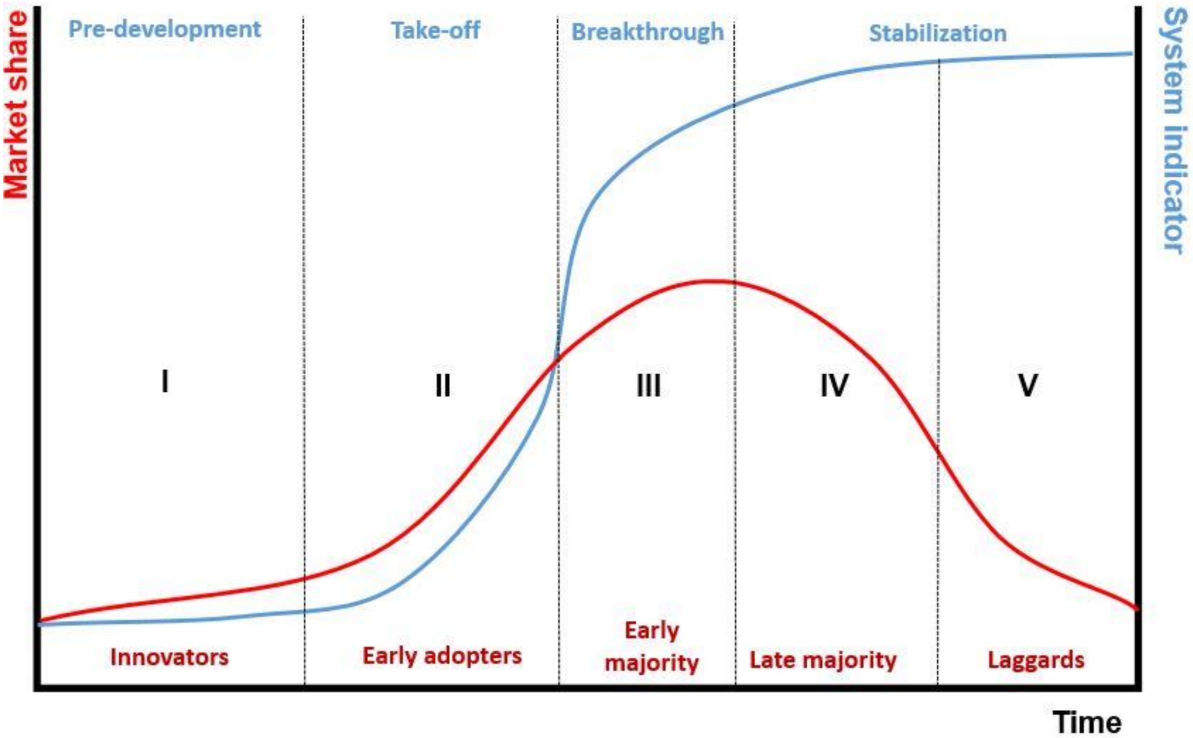


*Figure **7.1**: Conceptual comparison of transition theory (Loorbach, 2007, blue) and diffusion of innovations (Rogers, 2010, red).*

Discussion: transition phase of energy transition in the built environment in the Netherlands

The document analysis and the interviews resulted in a wide range of statements by stakeholders that indicate that the regime of the energy transition in the built environment is starting to shift; policy space is being created and exploitation of the current energy supply system is slowly being phased out (see Section **6.2.1**). It could be concluded that the energy transition in the built environment is now reaching its take-off phase. When applying a transition management perspective regime, it is being observed that stakeholders are translating the long term visions on the energy transition into concrete pilots, projects and policies, both due to pressure from the landscape level (strategic activities; long term visions, goal formulations (e.g. European Commission, 2010; Rijksoverheid, 2016b; SER, 2018) and by the emergence of sustainable innovative niches (operational activities*; 'societal, technological and institutional practices that introduce new structures, routines and actors'* (Loorbach, 2010, p.170) like the emergence of the sustainable innovative niche that is the main subject of this study; the tactical activities are being undertaken (Loorbach, 2010). These involve the removal of barriers (like the abolishment of the obligation to connect homes to the natural gas grid by the Ministry of BZK (Rijksoverheid, 2018c)) and the development of scenario's (as done by Netbeheer Nederland (CE Delft, 2017).

Discussion: transition phase of facilitation of hydrogen energy applications in the built environment in the Netherlands

These findings have implications for the determination of the phase in which the facilitation of hydrogen energy applications for the built environment is currently at. An increase in the awareness of the need for a different energy supply system resulted in a more explorative attitude towards sustainable innovative niches (Duit & Galaz, 2008), of which hydrogen energy applications are an example. Section **6.2.2** reveals that hydrogen energy applications are currently being explored by stakeholders and long-term visions are starting to be developed (CE Delft, 2017; Gigler & Weeda, 2018; SER, 2018). These are visible symptoms that show awareness of such applications as a sustainable innovative niche among landscape and regime level stakeholders A lack of shared visions on their position in the future energy supply system (R1; R10), and a lack of experience and trust (R6; R8) however result in a situation in which stakeholders are mainly involved in operational activities (Loorbach, 2010) and conducting small-scale experiments. Tactical activities, like removing legislative barriers and formulating concrete transition paths towards hydrogen energy applications have not taken place yet (Loorbach, 2010; R8).

Networks of frontrunners, in which stakeholders from different backgrounds are being set up and are starting pilots, such as HYDROGREENN (R2). They have a clear focus on the involvement of society and building trust and experience, but so far, the projects have not currently reached the phase in which these are crucial (see Section **3.3.4**). Here we see that decentralised authorities are willingly taking their roles, due to their proximity to society and their internal motivation to translate the landscape visions into policy and projects that are supported by society (R4/R5; R7/R10). The TSOs are having a crucial role in advising the decentralised authorities, as has been argued by them and, in this case particularly, the municipality (R3; R5).

When experience and trust with hydrogen energy applications for the built environment among both stakeholders and society increases, it is expected that an increasing amount of other stakeholders also are willing to adopt hydrogen energy applications (Kemp & Rotmans, 2004; Walsh, 2012), and which was also expected by the interview respondent (R6). A lack of trust and familiarity currently withholds customers to pay for those innovations. Both in a lab setting an during earlier pilots (Duurzaam Ameland, 2018), experiments with such boilers are already taking place and in the case study project is it is proposed to test such boilers in a domestic (real-life) setting. This resonates very well with a predevelopment phase among market stakeholders (Loorbach, 2007) Based on the minimal described characteristics of the phases in literature (Loorbach, 2007). According to other interview respondents, no actual implementation in the built environment has taken place yet although many initiatives are popping up (TKI Nieuw Gas, 2018). Actual implementation is seen as a symptom of the beginning of a take-off phase (Loorbach, 2007). In order for the take-off phase to start, facilitating regime stakeholders should formulate ambitions to upscale the already ongoing developments and to mobilise other stakeholders (Van der Brugge et al., 2005). As these activities, which resonate with the characteristics of a take-off phase described by Rotmans et al. (2001), have not yet taken place, hydrogen energy applications should be seen as a sustainable innovative niche in a predevelopment phase in the Netherlands.

Answer to sub-question 2

- *What is the current phase of the energy transition in the built environment in the Netherlands, and what is the current position of hydrogen energy applications therein?*

It can be concluded that hydrogen energy applications are a sustainable innovative niche in the energy transition in the built environment that is currently in a take-off phase, but due to a lack of shared vision and trust, large scale involvement of stakeholders and society and, simply, a lack of practical experience, hydrogen energy applications for the built environment themselves are in a pre-development phase. The reasons behind the findings above could be mainly derived from the complexity and uncertainty that is involved with the position of hydrogen as an energy carrier.

7.1.3 Opportunities and challenges of hydrogen energy applications in the energy transition in the built environment

The third sub-question aims at identifying challenges as well as opportunities that are involved with the implementation of hydrogen energy applications. **Chapter 2** addressed the practical opportunities and challenges, while the connected opportunities and challenges of an organisational-institutional nature have been addressed in Section **3.3**.

Discussion: distinction between practical and institutional opportunities and challenges
This clear distinction made in the theoretical basis of this study results in a strong perceived dichotomy between practical and institutional opportunities and therefore strongly resonates in the study, while in reality those two different categories seemed evolve smoothly into one another. The results outlined in Section **6.3** strongly confirm this suggestion, and that is why in retrospect, the theoretical framework of this study should have been structured differently and more attention should have been paid to the chicken-egg dilemma, which was mentioned in almost all the interviews. Therefore, this section addresses the main hypothesised (see Section **3.3**) and identified (see Section **6.3**) opportunities and challenges of hydrogen energy applications in one section.

Discussion: The consequences of complexity on energy planning
It could be argued that within the energy transition in the built environment, transition theory meets complexity science (e.g. Stoker, 1998; De Roo, 2010); the energy transition in the built environment might not only lead to a different energy supply system in physical terms, but is also expected to necessitate a different governance approach as the formation of such a new energy supply will enhance an increase in the number and the interdependencies of relationships between energy sources, energy carriers, energy supply, energy demand and energy planners that results in uncertainty (as stated in Section **3.3.1**), which is being confirmed by the interview respondents (R1; R3; R6; R9), as well as in the documents (SER, 2013; Rijksoverheid, 2016b). The shift from top-down organised combustion of fossil fuels towards a wide range of different alternatives that are dependent on the local context leads to the emergence of multiple, composite and dependent goals (De Roo, 2010) and it requires a more participative planning approach. Transition management is, according to Loorbach (2010), an appropriate governance approach to apply in complex governance contexts. Therefore it seems that this resonates very well with the theoretical framework and the chosen theoretical perspective is well applicable. Although these findings are valid for the entire energy transition, they also explicitly link to hydrogen energy applications in the built environment, as will be outlined below.

Discussion: uncertainty and the chicken-egg dilemma
As Campbell (2006) and De Roo (2017) argued, the energy transition [in the built environment] is not only a complex phenomenon, it is also deeply uncertain. Dynamic developments and complex interrelationships result in limited overview of stakeholders on what actions should be taken (Meadowcroft, 2009; De Roo, 2010). This is particularly true for the facilitation of hydrogen energy applications, following the results outlined in **Chapter 6.** Uncertainty on the development of hydrogen in the energy supply system results in what is called the chicken-egg dilemma by the respondents: first demand has to be generated to enable suppliers to produce hydrogen, but this demand only emerges when there is supply. A vicious, circular development emerges in which nothing really materialises (R1; R2; R7). Although such dilemmas were not really touched upon in the literature, they were identified as a main barrier for facilitation of hydrogen energy applications in general and for the built environment in par-

ticular, as there is a rather limited range in financial and knowledge resources among most stakeholders involved in this end-use sector (which corresponds neatly with Rotmans, 2004).

Discussion: involvement of society
Complexity and uncertainty result in the need for a certain approach for the involvement of stakeholders and society (which corresponds with the findings of e.g. Rotmans, 2004 and Nilsson et al., 2011). A lack of knowledge and experience results in societal, economical and institutional questions being difficult to answer (*'we don't have a clear picture of the safety risks yet'* (R6); *'there simply is no business case yet'* (R2; R0)**,** which consequently results in a lack of trust, acceptance and understanding among both the wider category of stakeholders and society itself (which resonates with the findings of Wüstenhagen et al., 2007 and Meadowcroft, 2009). The involvement of society as a challenge is strongly associated with the phase of the transition that has been determined in the previous section. And, *'as unknown means unloved'* (R8), this results in stakeholders being hesitating towards hydrogen energy applications for the built environment. Such barriers could be solved by the establishment of networks in which stakeholders from many different disciplines interact and collaborate to initiate and execute pilot projects to gain experience, which is exactly what HYDROGREENN and the NIB are aiming to do (NIB, 2017; R2). This approach corresponds with the argument of Kemp & Rotmans (2004) that the only way forward in the transition is a learning-by-doing approach with stakeholders from a wide range of backgrounds (Kemp et al., 2007). Research institutes were argued by the stakeholders to be crucial to overcome worries about safety and feasibility (R10). The message of safety and efficiency has to be experienced by society itself.

Discussion: legislative and regulatory framework
Another main category of opportunities and challenges is strongly connected to this. The legislative and regulatory frameworks are either incompatible with hydrogen energy applications for the built environment (which shows the necessity of fundamental, irreversible changes in the socio-technical system) or non-existent. For examples of such incompatible legislation, see Section **6.3.4**. Although this mainly a result of a lack of involvement of stakeholders and society (see above), it also poses new challenges for willing stakeholders to facilitate hydrogen energy applications. The sequence of the shaping of institutions as explained in Section **3.3.4** that institutional change is a slow process that *'fundamentally lags behind*' new developments (see e.g. Olsen, 2009; Meadowcroft, 2009; Mahoney & Thelen, 2010; Edquist, 2013) was well recognised by the stakeholders (R6; R7), which limits the acting space of stakeholders to experiment, as R8 (Gasunie) explained.

Discussion: institutional design of energy planning
The institutional design of the Netherlands with regard to energy transition in the Netherlands comprises both opportunities and challenges for hydrogen energy applications for the built environment. First, decentralisation of planning responsibilities was argued to be significant challenge (Gupta, 2007; Nadin & Stead, 2008) in Section **3.3.5.** During the interviews, it became clear that the decentralisation of responsibilities is recognised, in terms of knowledge and human resources but mainly in terms of financial resources. From the national level, it appears that decentralisation of responsibilities is a deliberately chosen strategy, as it is expected from municipalities to develop local and regional strategies and plans on the energy transition in the built environment (Rijksoverheid, 2016b; CE Delft, 2017). A major barrier with regard to the energy transition in the built environment that is experienced by both the province and the municipality, is a lack of financial means to upscale the transition (Gupta, 2007). The decentralised authorities both argue that the allocated financial resources do not correspond with the importance of the task that has to be executed in the coming decades (R5; R10). Although this challenge is recognised, it is not perceived as a large barrier (except for the financial resources). Due to the high degree of stakeholder involvement, the necessary knowledge is argued to be present at partnering stakeholders who are willing to share knowledge, and human resources are argued to be present at the

province if the municipal human resources become inadequate, such as consultancies and industries. On the other hand, some interview respondents see decentralisation as a way to bring in a local focus (R7/R10) which could also accelerate the facilitation of hydrogen energy applications.

Second, the role of the TSOs is an important issue related of institutional design. The interview respondents argued that because of their extensive knowledge and experience on 'the construction, management and maintenance' of the grid (R3), their advisory role will become more important. As an independent research document, it is suggested in this study that the role of the TSO should become more important and formal with regard to the energy transition in the built environment for this reason.

Discussion: availability of assets
Although not purposefully mentioned in the theoretical framework, the availability of assets provides many opportunities for hydrogen energy applications, as it makes them more feasible than some alternatives in certain situations. Especially the dense and well-maintained natural gas grid is argued to be an important asset that could function as a catalyzing element to implement hydrogen energy applications for the built environment (R3; R8). The tremendous potential of renewable energy is expected to be a valuable asset for the facilitation of hydrogen energy as well.

Answer to sub-question 3

- *What are the main opportunities and challenges for facilitation of hydrogen energy applications in the energy supply system of the built environment?*

The most critical and fundamental challenge towards the facilitation of hydrogen energy applications in the built environment could be argued to be the complexity of the context in which the energy transition in the built environment takes place. Complexity results in uncertainty, which results in limited levels of involvement of society and stakeholders. The deficiencies in and a lack of legislative and regulatory instruments result in limited acting space for those who do want to experiment with hydrogen energy applications. In the institutional design of the Netherlands, decentralisation could be a risk for coherent and structured approaches but also offers opportunities for a local focus and is thus not necessarily a barrier. The availability of important assets, like suitable infrastructure and oversupply of renewable electricity, are important opportunities for the facilitation of hydrogen energy applications.

7.1.4 Regime level stakeholders in the facilitation of hydrogen energy applications in the Dutch energy transition in the built environment

According to Geels (2011), the regime level in a transition is the analytical level of a transition that is of prime interest for transition management (also see Section **3.4**). Therefore, the fourth sub-question involves the discussion on which stakeholders could be considered regime level stakeholders in the transition towards the facilitation of hydrogen energy applications in the energy transition in the built environment in the Netherlands.

Discussion: the identification of regime level stakeholders
Like what has been argued in Section **3.5**, from a transition management perspective, regime level stakeholders are supposed to be involved in so-called tactical governance activities: such governance activities include conducting projects and shaping plans, institutions and regulations with a mid-term focus, while usually applying a tendency towards optimisation and exploitation to the existing energy supply system rather than applying an innovative and explorative attitude towards sustainable innovative niches (Loorbach, 2010; Van der Brugge et al., 2005). It has been hypothesised that niche developments may infiltrate the regime only when they contribute to the efficiency and optimisation of the existing system (Van der Brugge et al, 2005; Kemp & Rotmans, 2011) . Consequently, Kemp (2012)

argues that *'without regime actors [a transition] will not work'* (p.1), thus arguing that such stakeholders are crucial for facilitating hydrogen energy applications in the built environment.

Like what has already been suggested in Section **6.4**, it is the question whether or not the interviewed stakeholders from different (semi-)governmental organisations should be considered regime level stakeholders. Although all of them expressed to be monitoring sustainable innovative niches, practice shows they only very carefully seem to create conditions that enables the incorporation of the niche of hydrogen energy applications for the built environment into the regime

Discussion: Regime level stakeholders and their roles

It has been suggested in Section **3.6.2** that the provincial level corresponds with the regime level from a spatial perspective. To a large extent, this statement could be argued to be true; 'the facilitating and coordinative role' (R10) of the provinces clearly matches the characteristics attributed to regime level stakeholders. For example, the expressed activities of participating in knowledge networks, construction of financial instruments and facilitating interaction between stakeholders fit really well with tactical activities (Loorbach, 2010). Section **6.4** shows that the Province of Drenthe is aware of the supporting and stimulating role that it is expected to have based on theory, but it seems that they are rather unconscious how important such a role is in a transition. The provinces stimulate municipalities to come with bottom-up initiatives and are willing to collaborate on many issues (R7/R10). Currently, the provinces could be seen as crucial coordinative stakeholders in the current transition at a regional level. Coordination is needed to ensure a consecutive learning process in the region (see Section **6.5** and **7.1.5**).

It is questionable whether the municipality's role matches that of a regime level stakeholder. At the one hand, municipalities are responsible for coordinating local initiatives within the municipal boundaries and constructing financial stimulation instruments with a coordinative focus (R3; R4/R5) which fits with the tactical activities outlined by Loorbach (2010). On the other hand, however, municipalities are not expected to be able to foster long-term change in a transition as a whole; municipalities have a short-term focus that is aimed at executing and realizing local projects that serve the achievement of local goals (Gemeente Hoogeveen, 2018b; R4). This became clear in the case study, whereby the municipality was the driving force behind the *'development of a neighbourhood that fits well into the landscape'* (R4), but not behind the idea to fulfil the energy demand with hydrogen energy applications, which was consequently proposed by the Province of Drenthe (R7). The latter resonates strongly with the multi-level perspective on transitions by Geels & Kemp (2000) and the corresponding transition management activities by Loorbach, 2010), who state that at a local innovative ideas and projects are initiated and executed, but with a short-term focus (Loorbach, 2010).

Contrary to the theory on the multilevel perspective on transitions (Geels & Kemp, 2000), the higher-order national government authorities (Ministries) have characteristics of a regime level stakeholder as well. The national government and its organisations (the Ministries of EZK, BZK and I&W) are mainly landscape level stakeholders, which resonates with the multilevel perspective of transitions of Geels & Kemp (2000). Such stakeholders are involved in strategic activities like the formulation of long-term goals that anticipate on the transition. As Loorbach rightfully states: '[the national government is involved with] the overall development of the societal system' (Loorbach, 2010, p. 169). The same is true for the EU, which should be considered a typical example of a landscape-level stakeholder in its formulations of long-term goals and expressing a certain kind of urgency for the broad issue of sustainability (European Commission, 2010; R1). However, there are certain regime level, tactical, activities that are at the national government, as the adaptation of legislative and regulatory frameworks and distributing subsidies to projects of national importance is a national task (R7/R10; R6).These activities fit with *'developing programs, […] institutional regulations, organizing networks and representing certain inter-*

ests' (Loorbach, 2010, p. 169).

Additional to the three spatial levels of government authorities, TSOs (which are semi-governmental authorities) have a clear regime level role as well. Although TSOs traditionally have the task to construct, manage and maintain energy infrastructures and the obligation to do this the most efficient way (which could be considered exploitative) and they are not allowed to create policies, their advisory role in the facilitation process of hydrogen energy applications appears to be rather explorative and facilitative. TSOs actively participate in network organisations and pilot projects in the field of hydrogen, usually in the personification of their energy transition spinoff which is allowed to do such activities. TSOs are, as such, crucial in the execution of so-called tactical activities (Loorbach, 2010). The idea behind this development is that once sustainable niches that improve the system, and many TSOs expect hydrogen energy to be such a niche development (R3; R8; R9), they already have the necessary experience and trust to accelerate the transition. Therefore, RENDO, Alliander and Gasunie are all members of the core team of HYDROGREENN and, together with TenneT, a member of the Hydrogen Coalition. In their roles, TSOs have a strong advisory role on government authorities and can therefore influence their choices.

From the interviews it became clear that other stakeholders can take such a regime level role as well, for example housing corporations and project developers. They are in that respect regarded to have a more exploitative attitude, as their main task is to provide affordable homes to society. R1 argued that housing corporations are not really willing to participate in the transition yet, as it necessitates them to increase rents. Such an attitude is resonating well with the characteristics of regime level stakeholders in the literature: they are explorative, looking for new innovation, developed niches, test with it, but in the end, their main activities are apparently exploiting the current system. As long as nobody is willing to pay for it, innovations will not be taken into the regime level.

Discussion: diffuse role division and attitudes of stakeholders in the case study

From an analytical perspective on transition management, such as applied in Section 3.5, the findings that stakeholders can take different roles, corresponds neatly with the suggestion made in Section **3.6**, which comprises that stakeholders can be active at different levels of transitions. For example, the national government authorities, provinces and municipalities are all involved in stimulating niches and facilitating projects, just at their own jurisdictions. Although the roles in the pilot seems to differ from theory, the described roles in the transition by the interviewees are closely related with the roles of Rotmans et al. (2001), as in the transition phases in which the transition currently occur, government authorities should currently apply a facilitating and catalyzing role (Rotmans et al., 2001).

In the case study of Nijstad-Oost/Erflanden, the municipality, RENDO and various members of the core team of HYDROGREENN are expected to have a key executive role (when the project continues as is currently proposed; R2; R4/R5; R10). The Municipality of Hoogeveen and RENDO could both be seen as stakeholders who have characteristics of a regime level stakeholder, but in the project, only RENDO has a role that could be seen as regime level role. In the preparatory stage, the Province of Drenthe had a very important role in connecting the municipality and HYDROGREENN, which is something that resonates with the tactical activities described to be characteristic for the regime.

As such, it could be justifiably argued that the roles in the case study largely correspond with the suggestions made in **Chapter 3:** the municipality has initiated the new neighbourhood and facilitated the hydrogen energy applications part of it, and should in this perspective be seen as a niche level stakeholder. The role of the Province of Drenthe is to facilitate interaction and to coordinate pilots, which is exactly what they did and still do in the case study (Rotmans et al., 2001; R7/R10). In the case study, they did exactly what could be expected from Section **3.3.5.** The role of the Municipality of Hoogeveen in the hydrogen energy applications part is rather unclear, both due to stage of development of the project and tactical activities that belong to the municipalities' task.

Discussion: institutional change
However, it is uncertain whether the extent to which these stakeholders really are regime level stakeholders is corresponding outside the context of this particular case study (which is not yet realised) and with respect to upcoming legislative changes. This is especially relevant for the role of the municipality, as the upcoming Environmental Act will significantly enlarge the role of the municipal level in the energy transition in the built environment, because of the implementation of the new Environment Act and the resulting obligation for municipalities to construct Environmental Visions for each neighbourhood by 2021 requires a broader and more long-term focus (R4/R5; R10), which follows Needham (2005). Such a focus then again corresponds with tactical activities. This might result in a new relationship between provinces and municipalities in the near future. On the one hand, it might be expected that role of the provinces will shift from an initiating towards a more stimulating one, while at the other hand it might be argued that the need for supra-municipal coordination will become even bigger and coordination will thus become more important. It is currently unclear how this will develop.

Answer to sub-question 4

- *Which stakeholders are regime level stakeholders in the governance of the energy transition in the built environment in the Netherlands?*

The regime level of the energy transition in the built environment consists of both (semi-)governmental and private stakeholders. These are the stakeholders that are involved in the so-called tactical activities (Loorbach, 2010), and these stakeholders are able to induce as shift in the existing regime in case the implementation of hydrogen energy applications will start. Among those, the Provinces and the TSOs are clearly and dominantly regime level stakeholders. However, the municipalities and national government organisations also have some characteristics of regime level stakeholders. The roles of the TSOs is rather remarkable, as they share the same attitude and are subject to the same developments as the other regime level stakeholders (Duit & Galaz, 2008), but their formal competences to actually foster change are very limited. What is also quite remarkable is the conclusion that the roles of other stakeholders which have been mentioned by respondents and in documents also share characteristics of regime roles, like housing corporations and project developers; they tend to have a rather exploitative attitude. The assumption that stakeholders could be active at multiple levels has been confirmed: the ministry is active at the landscape level as well as the regime level and the industry is involved at the niche and regime level.

7.1.5 From niche to regime: explorative attitude of the regime stakeholders

In Section **3.5**, Elzen et al. (2004) argue that the regime level is subject to changes from both top-down pressure from the landscape and by bottom-up pressure from niches that strive for momentum to infiltrate the regime.

Discussion: top-down and bottom-up pressure on the regime
What is observed however, is that due to the multi-level involvement of different stakeholders, in practice it turns out that sustainable innovative niches get the attention of regime level stakeholders by both the stimulation of (semi-)government authorities themselves and the more 'traditional' market innovations. Niches are introduced at the regime level via the energy sector but also via the facilitating and stimulating role of the provinces. Although top-down pressure from the ministry or EU is explicitly noticed in the case study project, implicit pressure is exerted on different regime level stakeholders via

stimulating and pressure via the long-term visions of the EU and the Ministries; their long-term visions contribute to the awareness of regime level stakeholders for change. For the energy transition in the built environment in general, the Netherlands adopted a time scale of more than 30 years, which is a symptomatic example of a long-term landscape focus. By signing documents like the Energy Agreement and the Climate Agreement, the national government authorities, TSOs, influential societal organisations and market stakeholders force themselves, as well lower-level authorities and stakeholders to apply an explorative attitude towards sustainable innovative niches.

Like what has been outlined in the previous section, theoretically regime level stakeholders are only willing to consider implementation of sustainable innovative niches if they believe that a niche development contributes to the efficiency or overall performance of the system. Some level of clarity on the outcomes is usually necessary to achieve this, in order to adequately estimate the feasibility of investment, which has also been mentioned by the interview respondents. The distinction between explorative stakeholders and exploitative stakeholders signs itself off very clearly within this regard: it seems that semi-public authorities are more explorative and market stakeholders are more exploitative. This remarkable difference could be attributed to the different roles money and profit play within the nature of these organisations. Provinces, municipalities (and to some extent, the TSOs) have lower financial barriers towards facilitation of new niche developments in general and are also thought to be more willing to put such developments into a wider perspective 'the general good'. This finding matches the prerequisites for regime level stakeholders to apply an explorative attitude (Duit & Galaz, 2008, see Section **3.4.2**). An interesting suggestion that has been made in the interviews is for public stakeholders to act as launching customers. This creates demand among other stakeholders and lowers the threshold for regime level stakeholders to apply an explorative attitude towards hydrogen energy applications, both among (semi-)public and private stakeholders. Such creation of demand is mentioned multiple times by the public national and provincial levels. It is seen as one of the crucial instruments to stimulate bottom-up initiatives. It corresponds strongly with the ideas of Kemp & Rotmans (2004).

This stimulating and coordinating role of the provinces and TSOs could be seen as the necessary link between the regime and the niche level in a transition perspective (Geels, 2011). Provinces, and to a lesser extent municipalities, apply an explorative attitude towards sustainable innovative niches, which is needed for more exploitative stakeholders to gain trust and knowledge on hydrogen energy applications in the built environment. This results in these niche developments gaining momentum. Once such niches get adopted by exploitative stakeholders, the regime level is forcing itself to a shift. These observations resonate strongly with the ideas on development of sustainable innovative niches and diffusion of innovations (see e.g. Rogers (2010) and Walsh (2012)).

What is equally important in transition management to influence the regime level, and this has been mentioned both in the literature (Loorbach, 2010) and by the interview respondents, is the conducting of a consecutive process of reflexive activities. These activities mainly show itself as learning processes, which aim at creating and sharing commonly understood knowledge, gaining experience and fostering the exploration of new sustainable innovative niches. Additional to the regime level stakeholders themselves and the niche developments themselves, research institutes have been argued to play a key role in these processes. Reflexive activities are continuous process; a consecutive cycle of learning. Clear and active communication can contribute to profiling and are crucial as well to change the attitude towards hydrogen energy applications among stakeholders. Such profiling and publicity contributes to increase learning within society by publicity via media, including consecutive learning from near-future projects.

Provinces and municipalities appear to be willing to support sustainable innovative niches and show this by coordinating, steering and guidance for new pilots to focus on. Consecutive learning processes turned out to be important; and in these processes the TSOs and research institutes are expected to have a key role, additional to the decentralised authorities. Expert-knowledge is not required by the governmental stakeholders in the transition, since they are mainly involved in coordinating and stimulating projects. If necessary, knowledge will be obtained externally from (consultancy) market stakeholders. The case-study showed that stakeholders are mostly willing to cooperate and are aware of their interdependencies. Diversity of involved disciplines is still limited to governmental parties in the region, but seems not to be experienced as a barrier. The same applies to differences in perspective between the ministry and provinces.

Answer to sub-question 5

- *How are stakeholders responsible for the regime level of the energy transition in the built environment being influenced and changed by niche developments in the Netherlands?*

Regime level stakeholders are influenced by top-down pressure from the landscape level and by bottom-up pressure from the sustainable innovative niche of hydrogen energy applications for the built environment, although in practice it appears that such developments mainly occur as a result of reflexive transition management activities, which comprise the emergence of a consecutive learning process. In these processes, the help from research institutes is crucial for a trustful and neutral communication of results. Government authorities who apply an explorative attitude towards sustainable energy niches could help to create demand by acting as a launching customer.

7.1.6 Identification of opportunities and challenges in the governance of the Dutch energy transition in the built environment at the regime level

Section **6.6** encompassed the execution of a SWOT analysis on the governance structure for facilitation of hydrogen energy applications in the energy transition in the built environment in the Netherlands. The analysis resulted in a SWOT matrix, which could be used to answer the sixth sub-question:

- *Which opportunities and challenges for hydrogen energy applications are present in the governance of the energy transition in the built environment in the Netherlands to foster the facilitation of hydrogen energy applications for the built environment at the regime level?*

Answer to sub-question 6:
The SWOT analysis has resulted in the observation that there is willingness of both public authorities and market stakeholders to experiment with hydrogen energy applications (largely because of a recent growth of awareness on the need for change and the opportunities hydrogen can offer to cope with the challenges of this necessary change) and the Netherlands have suitable assets to do so, but also that still very much is uncertain on how this could be concretely materialised and that there is a lack of concrete goals and ambitions to really induce this change on the landscape level.

A combination of the awareness on the availability of assets, the high investment costs that some of the alternative sustainable energy alternatives for the built environment involve, and a widely-shared conclusion that hydrogen is expected to become a key element of the Dutch energy transition, have resulted in a shift in focus on the regime level; electrification is no longer seen as the end option for the built environment, but sustainable gases like hydrogen are subject to increased attention among the regime level stakeholders. The biggest challenge for hydrogen energy applications (and hydrogen in general) lies in the uncertainty on when the chicken-egg dilemma, which is now strongly connected to this energy carrier, will be cut through. It is not a question if this will happen, only when this will happen. For large-scale implementation in the built environment, however, the availability of sufficient sustainably-produced hydrogen is seen as a big challenge.

To achieve cutting-through of the chicken-egg dilemma and ensuring the availability of sufficient sustainably produced hydrogen, respondents ask for clear, long-term and unambiguous goal setting on the (inter)national scale level: crucial choices have to made to invest in large-scale renewable electricity production entirely aimed at electrolysis for green hydrogen production. Since the Netherlands have a strong position in the field of hydrogen in general and a lot of potential for wind energy, this opportunity is necessary to exploit. This, in combination with sharing the results of successful pilots, could enhance acceleration in the facilitation process of hydrogen energy applications for the built environment by regime level stakeholders.

7.2 Conclusion to the main research question

As all sub-questions have been answered, the main research question of this study can be formulated an answer to. This question was formulated in the following way:

- *How could hydrogen energy applications for the built environment be facilitated by regime level stakeholders in the energy transition in the built environment in the Netherlands?*

Corresponding with the transition management cycle as applied by Loorbach (2010), regime level stakeholders are characterised by their involvement in tactical activities: translating long-term landscape visions on the energy supply of the built environment into mid-term focused plans, projects and strategies. In the current take-off phase of the energy transition in the built environment (in which hydrogen energy applications are determined to be a sustainable innovative niche in a predevelopment phase) a facilitating and stimulating role towards hydrogen energy applications suits the activities of regime level stakeholders (Rotmans et al., 2001). These stakeholders are hypothesised to be influenced by the long-term focused strategic activities by the EU and the national government authorities in the Netherlands, as well as bottom-up by the development of various hydrogen energy applications by bottom-up, sustainable innovative niches via operational activities from society and the market. All these activities take place in a deeply complex and uncertain context, in which the entire energy supply system for the built environment evolves from a top-down, centrally organised system towards a system in which bottom-up and top-down supply of energy will probably both be significant and in which the options for energy supply of the built environment will probably consist of a wide range of different options each having different rates of feasibility in different situations. This necessitates fundamental changes in the institutional design of the energy planning system; as such interdependencies require a planning approach that is able to cope with multiple, dependent goals that have implications on multiple scale levels; multilevel governance is a key element of such an approach.

Sustainable innovative niches are argued to be *'the seeds of a transition'* by Elzen et al. (2004). Hydrogen energy applications are an example of such a sustainable innovative niche. The attributes of hydrogen as an energy carrier to cope with the most fundamental problem of the energy transition and the abilities of hydrogen for sector-coupling , as well as the availability of significant assets that should otherwise be removed are significant and important opportunities that speak in favour of hydrogen energy applications for the built environment. Therefore hydrogen energy applications deserve the attention and resources from regime level stakeholders in the energy transition to be investigated as a serious and feasible option for the built environment. To do so, regime level stakeholders have to apply an explorative attitude towards hydrogen energy applications for the built environment and actively look for collaboration with landscape and niche level stakeholders from various backgrounds. This in turn might lead to a greater involvement of other stakeholders and society.

What became clear in this study is that many stakeholders are not exclusively landscape (conducting strategic activities), regime (conducting tactical activities) or niche level (conducting operational activities stakeholders and actually are involved in either both strategic and tactical or both operational and tactical activities. Both (semi-)public and private stakeholders seem to have different roles in the same developments. This observation was also made in the different semi-structured interviews and could be seen as both an opportunity and a challenge for the facilitation of hydrogen energy applications in the built environment. In such a complex governance context, stakeholders could be at the one hand involved in operational niche level activities such as the development of Nijstad-Oost/Erflanden as the first proposed hydrogen energy based neighbourhood of the Netherlands (applying an explorative attitude). At the same time, they also have to balance the opportunities and challenges of both hydrogen energy applications and other sustainable innovative niches as the involvement of stakeholders and society is crucial because there will otherwise be no business case and a lack of trust (applying an exploitative attitude). Therefore, innovative stakeholders (mainly public stakeholders) could, apart from applying an explorative attitude, act as launching customers for such applications to create a first, basic demand and to show that hydrogen energy applications for the built environment are working in practice and not only on paper. Such an approach and a basic demand enables other stakeholders to remain explorative and to improve the efficiency, feasibility and affordability of hydrogen energy applications in order to gain experience and trust with hydrogen energy applications among both more exploitative stakeholders and society in general. Consequently, such an approach could make hydrogen energy applications more attractive for these more exploitative stakeholders. Such an approach could eventually result in the large-scale implementation of hydrogen energy applications.

However, it is important to maintain continuous and consecutive reflexive learning processes to monitor improve and share knowledge, trust and experience within a highly collaborative institutional framework. Such collaboration should lead to the execution of multiple pilots and projects on the short term, which results in improved knowledge and an increase of acceptance and trust. For a local focus and for an adequate level of weighing different sustainable energy alternatives, the municipality is a crucial and directive stakeholder. Provinces and TSOs, as well as research institutes and consultancies, are then crucial to coordinate and advise on the different projects and pilots in a structured way.

As the energy transition in the built environment is currently undergoing very dynamic and rapid developments, it is important that on the field of hydrogen energy a network of important stakeholders form different background will be formed and mobilized. Such developments are already ongoing, and are important to structure and direct the different experimental pilots with a short term showcase focus into a concrete, mid-term focused strategy that is coherent and consistent and allocates the means that are corresponding with such ambitions.

Stakeholders are expected to face several challenges in the approach outlined above:

- A high degree of complexity of the context in which the energy transition in the built environment occurs. This is the result of an increase in both the number and interdependencies of relations between energy demand, energy supply, energy sources, energy carriers and stakeholders in space and time, which results in a high degree of uncertainty;
- A framework of shared visions, interests and ambitions on the position of hydrogen in the general energy transition is needed to formulate answers and strategies on the chicken-egg dilemma that is associated with hydrogen;
- A legislative and regulatory framework needs to be developed on hydrogen as an energy carrier in all end-use sectors to enable stakeholders to become more explorative towards hydrogen as an energy carrier;

- A lobby on an international scale level is encouraged in order to raise awareness in surrounding countries (who so far tend to have a different focus in the energy transition) on the opportunities of hydrogen as an energy carrier and to achieve an alignment of interests on this scale level, which could result in the break-through of the chicken-egg dilemma associated with hydrogen.

Although it is very unlikely that hydrogen energy applications will replace the current energy supply system for the built environment entirely, the described strategy might result in hydrogen energy applications for the built environment being embedded on the 'palette' of a sustainable future energy supply system, additional to other sustainable energy alternatives. Ultimately, when this energy supply system gets embedded in society, the regime will irreversibly shift towards a sustainable energy supply system in the built environment. The strategy is visualised in Figure **7.2**, which could be seen as an improved version of the conceptual framework discussed in Section **3.6**.

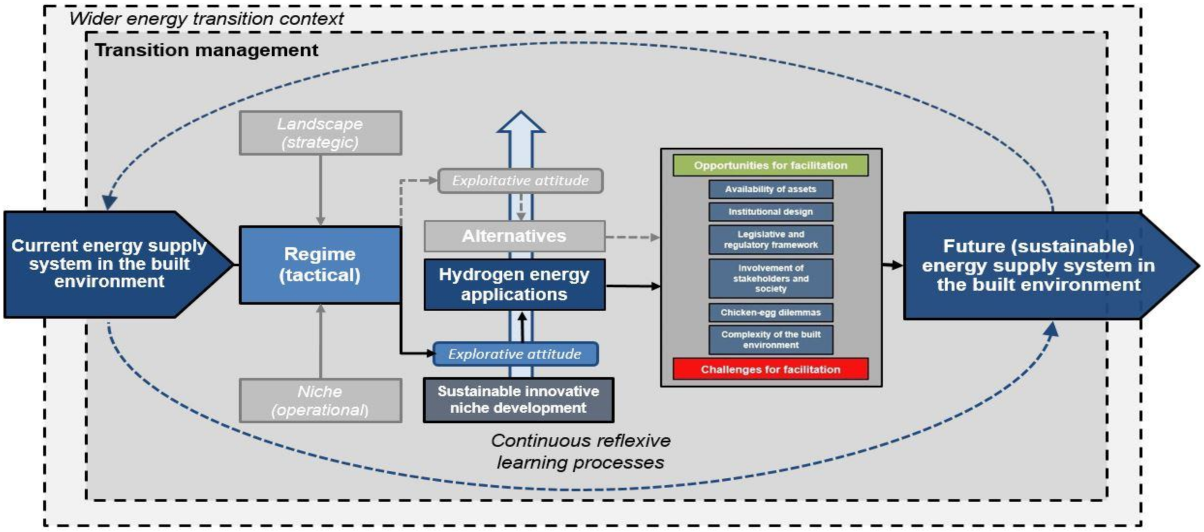


*Figure **7.2:** Conceptual visualisation of the facilitation of hydrogen energy applications into the (regime of) the future (sustainable) energy supply system of the built environment.'*

7.3 Policy recommendations

This study identified the main opportunities and challenges to the implementation of hydrogen energy applications in the built environment and determined that hydrogen energy applications in the energy transition in the built environment in the Netherlands are currently a development that is in the predevelopment phase in a transition context that is starting to take off. Although it has been concluded that it is still quite uncertain what the potential of such hydrogen energy application is on the long term, some policy recommendations for government authorities could be drawn up in order to be able to strengthen their feasibility as a sustainable energy alternative in the Netherlands. Some of the policy recommendations are directed towards the national government, while others are directed towards the regime level stakeholders.

- Strengthen and formalise the advisory role of TSOs

Currently, the TSOs have a rather strictly defined set of tasks, which is fully aimed at executing the orders of government authorities and market stakeholders. In practice, it seems that there is a strong advisory component in the task of the TSOs as well because their knowledge of the nature and the capacity of the infrastructure is better than that of anyone else. In order to reduce the complexity connected to the feasibility of different sustainable energy alternatives and to ease decision-making in the energy transition in the built environment, the advisory role of the TSOs should be formalised. By assigning a corresponding formal status to this valuable knowledge, it is expected that the decisions have a more long-term focus and are involved with a more balanced assignment of social costs to the different stakeholders.

- Take away legislative barriers

Currently, there are some important legislative barriers for regime level stakeholders to facilitate hydrogen energy applications in the built environment. A good starting point for the removal of such barriers would be to include hydrogen in the Dutch Gas Act as a gas that is allowed to be transported by TSOs under their legal competences. This would formalise the potential role of hydrogen as an energy carrier in the grid and enable stakeholders to start the construction of a backbone hydrogen infrastructure.

Additionally, it would be a good idea to enlarge the SDE+ regulations by including conversion of renewable energy carriers into other renewable energy carriers. Doing so would make it more financially attractive to invest in green hydrogen production, which would be beneficiary for creating demand for hydrogen in all end-use sectors.

- Formulate an unambiguous, coherent long-term vision that is both clear and flexible on the energy transition, while providing the necessary resources to implement it

A big challenge that has been expressed by many stakeholders is the lack of a clear long-term vision on the energy transition, although such a vision is often argued to be crucial. This long-term vision should be at the one hand setting clear, coherent goals and priorities, but at the other hand remain flexible to be able to incorporate new niches and leave room for optimisation on the local context. Additionally, setting clear and unambiguous goals also involves the allocation of resources that match the ambitions for the translation of long-term goals into mid-term plans and short-term concrete projects.

- Profiling and publicity

It is important that frontrunners who execute pilots with hydrogen energy applications in the built environment share the successes of these pilots and express the opportunities that such applications offer. By profiling the Netherlands (or a region within the Netherlands, like the NIB does) as an ideal place for hydrogen-based energy supply, more exploitative stakeholders could be enabled to become aware of the feasibility of hydrogen energy applications and start exploring them by themselves. This is true for market-based stakeholders, but also especially so for (semi-)governmental stakeholders

Such profiling might also attract international attention, which could be helpful to solve the chicken-egg dilemma that is inherently connected to hydrogen as an energy carrier (according to the interview respondents). Solving the chicken-egg dilemma could not only be done by the Netherlands themselves.

According to Loorbach (2010), media play a key role in publicity and profiling and these are indeed capable of communicating messages from experiments and pilots into society. Clear and honest communication is thereby needed, to make society aware what are the pros, cons and consequences of hydrogen energy applications for people.

Other means of publicity could be equally useful. For example, attention to hydrogen energy applications (and other sustainable energy alternatives) could be given in education. This is important as the energy transition is a long-term development, of which the consequences will be mainly tangible for next generations.

- Provide ample room and stimulate pilots, while providing the necessary resources

Last, in order to successfully upscale hydrogen energy applications for the built environment and exploit their potential, it is important that stakeholders keep conducting and initiating pilots to further involve society and to enhance trust, experience and practical knowledge. To successfully conduct pilots, a sufficient supply of knowledge and human and financial resources should be guaranteed. If the knowledge is not present at the organisation itself, hiring external knowledge from consultancies is recommended, as it can both assist in finding solutions but also broaden the stock of knowledge that is present in an organisation.

8 Reflection and recommendations for further research

This chapter reflects on the findings of this study, the research process and poses limitations in the approach that has been used to conduct this study. The findings of the study and the limitations outlined in this chapter are then used as starting points to formulate recommendations for further research.

8.1 Findings

The findings of this study largely meet the research objectives that were set up beforehand and outlined in Section **1.2.** A better understanding of the position of hydrogen energy applications has been achieved, which resulted in the development of a set of recommendations for stakeholders who are involved in the governance of the energy transition in the built environment in the Netherlands. The findings might contribute to a reduction in uncertainty and provide a better understanding on how governance issues in the energy transition in the built environment might be overcome, as well as a framework of reference on how willing stakeholders can foster change by demonstrating an explorative attitude and participating in reflexive activities. Therefore it can be justifiably argued that this study successfully achieved its goals that make it relevant for society and academia (also see Section **1.3**). One of the aspects that this study was argued to be a contribution to in Section **1.**3 has been insufficiently investigated, however: the extent to which this study contributes to transfer of ambitions and lesson drawing on an international scale level. The main reason for that that was identified in this study is the different focus of other countries in the energy transition (due to the earthquake-related problems in Groningen that provides a strong intrinsic motivation to abolish gas extraction, R6). A lack of time to expand this study into the international context also inhibited the researcher from further achievement of this socially relevant objective.

To achieve more balanced and inclusive findings, it could have been done better by also explicitly including other sustainable energy alternatives into the research design (and not solely focusing on hydrogen energy applications). Doing so was beyond the scope of this study, however, because of time limitations. Another limitation to the findings is that hydrogen energy applications were not adequately defined before conducting the research; no decision was made to focus on a certain scale level or type of application, which resulted in unfocused questions and answers by respondents, as well less unambiguous results.

The dynamic developments in the energy transition in the built environment provide an important limitation to the relevance of this study's findings. During the period this research has been written, hydrogen energy applications got increasing attention in the media and in politics. This could have influenced the views of respondents within the course of the research, but also result in the fact that the findings might be of less relevance for science society shortly after the finishing of the research. This limitation is inherent to research subjects that are prone to quick and dynamic developments in their context.

Although this study's main subject is on hydrogen energy applications, based on the interviews and documents it might be expected that the study would also be to a large extent applicable for other sustainable innovative niches on energy alternatives for the built environment in the context of the energy transition.

8.2 Methodology

Although **Chapter 4** justifies the chosen research approach to conduct this study, there are some comments related to the methodology that could be made in retrospect. Like Strauss & Corbin (1998) and Flyvbjerg (2001) already indicated, it is important to acknowledge that the results of qualitative scientific research are always subject to interpretation by the researcher and that the content of the analysed documents and interview transcripts are subjective interpretations from their experiences and perspectives. Therefore, it is important to critically assess the following points when interpreting the results of the study (Flowerdew and Martin, 2005):

- Position of the researcher: During semi-structured interviews, the research could unintentionally steer the behaviour and answers of the respondent. Aspects of physical attitude and asking suggestive questions are examples of such behaviour of the researcher. In retrospect, when checking the interview transcripts, it appeared that sometimes suggestive questions have been asked to collect information that would be of interest for the study. Therefore, it could be the case that respondents sometimes had too little space for own input.
- Interpretation of the raw data: Both in the documents and the semi-structured, there was a clear focus and goal of the research to collect certain types of data. Therefore, it could be the case that the research passed certain elements that are of importance to the respondent but were not given attention in the interview guide or in the interview themselves. It could be the case that respondents did interpret some of the questions differently than they were intended. Such situations were prevented by asking the respondents for own input at the end of the interview. A lack of a clear definition of hydrogen energy applications could however have resulted in incomprehension between the respondents and the researcher.
- Subjectivity of the researcher: The researcher is selecting the documents and respondents, formulates the questions and selects the important elements in documents and is also interpreting the data. As such, there are three moments at which the researcher determines which data are important and which are not. There is a risk of leaving important information out of the analysis. To tackle this risk, a wide selection of different stakeholders was asked to participate in this study.
- Generalisation of the results: As this research focuses on a single case study in a single context, there is a fundamental risk that the results are also only valid for this single case. It has to be taken into account that such an approach might result in a subjective and biased view towards the broader research topic. It could well be the case that a set of interviews with different respondents from the same organisation would result in quite different outcomes. Generalisation of this study should therefore only be done with extreme care. As mentioned before, great caution should also be applied when generalizing the results in a different context than the Dutch context due to the different institutional designs of energy planning in other countries.

Additionally, there are some points of attention regarding the applicability of the case study approach that has been used for this study. Although it prevented an uncoordinated range of separate interviews and a lack of boundaries to the study subject (which is obviously undesirable from an academic point of view), it also resulted in some difficulties. The first issue is that the chosen case study is actually more an ongoing planning process rather than a real, tangible project that already exists. As such, it is hard to speak of success or failure of the chosen sustainable energy alternatives, which make it hard to base meaningful recommendations on the basis of the case study. It would have been better to also focus on at least one project that has been finished or, at least, is physically present. To compensate for this and to put the case study in a broader perspective, the additional interviews with representatives of research institutes and TSOs provided a useful tool.

Another issue is the future-oriented nature of this study. It is important to understand that the statements that are made by respondents in the interviews are often, if not always, based on personal views and experiences. These are subject to change; stakeholders can influence each other's views and time can change perspectives of stakeholders. These issues already became clear in the double interview in which two stakeholders (R4 and R5) from the same organisation were simultaneously interviewed.

The last point of reflection is the fact that this study was conducted during an internship at Royal HaskoningDHV, which is a well-known consultancy firm in the Netherlands. It offered the precious opportunity for the researcher to immediately become part of the network, which provided access to all the relevant sources and stakeholders. However, this also results in a risk that stakeholders are reluctant to share all information with the researcher. After all, stakeholders might think their knowledge and ideas are going to be exploited by the consultancy firm to make profit. Although the researcher did not experience the semi-structured interviews in this way, it is a risk that should be kept in mind when reflecting on the relevance and reliability of this research.

8.3 Recommendations for further research

Based on the conclusions that have been formulated in **Chapter 7** and the considerations with regard to the findings and methodology outlined above, the following recommendations for further research on the position of hydrogen energy applications in the energy transition in the built environment could be made:

- In retrospect, this research would possibly have been more valuable when a case study project was included that is already present in practice. Hence, it is strongly recommended to investigate whether the same conclusions would be drawn if, for example, the pilot on Ameland (Duurzaam Ameland, 2018) would have been used.
- Although the application of transition theory and management has proven to be a suitable way for analysing the facilitation of hydrogen energy applications in the built environment, there are numerous other approaches that could applied to analyse such a change. Strategic Niche Management (e.g. Kemp, 1998; Caniëls & Romijn, 2008) and Ecological Modernisation (e.g. Spaargaren & Mol, 2000) are examples of such approaches that could offer interesting insights to complement the findings of this study.
- One of this study's weaknesses is the limited focus on the financial feasibility of the facilitation/implementation of hydrogen energy applications. It would be recommended to get more insights in these aspects, especially with regard to the position of hydrogen energy applications relative to other options (e.g. those mentioned in Section **2.4**) to get a more complete analysis.
- A wider study that focuses on hydrogen energy in all energy end-use sectors from either a transition perspective or another future-oriented perspective would be interesting to get more insights in the potential for sector coupling.
- A more theoretical study on the identified similarities between diffusion of innovations and transition theory and management would be of interest for the fields of spatial planning, public administration, management and numerous other disciplines in social sciences.

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Appendices

Appendix 1: Operational processes of other sustainable energy alternatives

Appendix 1 provides some background information on the five main alternatives to hydrogen energy applications discussed in Section **2.4** of this study: **heating networks**, **solar boilers**, **heat pumps (all-electric)**, **geothermal heat** and (other) **energy storage systems** (after TNO, 2017), as well as their main opportunities and challenges. All of these have competitive advantages and disadvantages in relation to hydrogen energy applications, depending on the situation-specific characteristics of the built environment.

Heating networks

Heating networks are networks of pipelines through which hot water, fed by residual heat from industries and power plants, is distributed (Rezaie & Rosen, 2012; Fang et al., 2013). This heat can be considered the useful reuse of exergetic value of endothermic processes when the heat is released by endothermic processes (Van Kann, 2015; see **Glossary**). For the Netherlands, this provides promising solutions for the heat demand in residential, commercial or industrial neighbourhoods or establishments with a low-temperature heat demand that are located in the relative vicinity of such heat-producing facilities. The operational process behind district heating is steered by using the residual heat to heat water that is transported through a pipeline system to a heat transfer station, where the temperature is monitored. From there, it is transported through the adjacent neighbourhoods or building(s) where it is used for space heating and tap water heating (Rezaie & Rosen, 2012). District heating is only useful for areas that are located in the relative vicinity of such heat-generating plants, although it is a very robust way to make efficient use of residual heat that would otherwise be lost (Raven & Verbong, 2007; Fang et al., 2013; Connolly et al., 2014). Heating networks could be used in combination with hydrogen-based stationary fuel cells or combustion plants (Fang et al., 2013; Dodds et al., 2015).

Solar boilers

Solar boilers are appliances that collect thermal solar energy to heat water. They can be used to generate heat for space heating and for tap water heating. The heat-collecting appliance of a solar boiler is installed on the roof of a building in the same way as a solar PV-panel. This appliance, filled with a transmitting fluid, is connected with a pipeline that runs through a tub in which hot water is stored (Chapman, 1980; Caird et al., 2008). Hybrid solar boiler systems do also exist. In such a system the tub is also connected with a fuel combustion boiler or a heat pump (Carotenuto et al., 2017). In the climate conditions of the Netherlands, this is necessary to have hot tap water and space heating during winter as solar heat alone will not be sufficient during the colder winter months (MilieuCentraal, 2018).

Heat pumps (*all-electric*)

Heat pumps are appliances that transfer thermal energy in the opposite direction compared to the natural situation. In the Netherlands, this option is often called the *all-electric* option (Rijksoverheid, 2016b; SER, 2018; Gigler & Weeda, 2018). Heat pumps are used to fulfil both space heating and tap water heating demands. There are many different types of heat pumps, but all types share this same principle (Scoccia et al., 2018). All heat pump types require electrical energy to operate. Ground- and water-source heat pump systems are significantly more efficient than other systems, because the soil and water generally have a fairly constant temperature (Omer, 2008). Hybrid systems do exist. In such systems, the heat pump is also connected with a fuel combustion boiler or a solar boiler system that is able to generate extra capacity when heat demand is high (e.g. during the Dutch winters). The table below shows the different types of heat pumps that can be used for space and tap water heating in the built environment. It is also possible to connect heat pumps to stationary fuel cells, like described in Section **2.2.1.**

Heat pump type	Operational process
Air-air heat pump	Heat from the outside air to heat indoor air (Bertsch & Groll, 2008; Pearson, 2010).
Air-water heat pump	Heat from the outside air to heat a central heating system based on water (Bertsch & Groll, 2008; Pearson, 2010).
Water-water heat pump	Heat from water to heat a heating system based on water.
- Surface water heat pump	Heat from surface water is transported through pipes in a building to heat a central heating system based on water.
- Ground-source water heat pump	Heat from a fluid transported through the underground to heat a central heating system based on water (Sanner et al., 2003; Omer, 2008).
▪ Closed system, vertical heat pump	Double loop system. Heat from a fluid that is transported to the deeper underground soil and then up again, where it is used to heat a central heating system based on water (Omer, 2008; Yang et al, 2010)
▪ Closed system, horizontal heat pump	Double loop system. Heat from a fluid that is transported through a horizontal system of pipes and then into the heat pump installation, where it is used to heat a central heating system based on water (Omer, 2008).
▪ Open system	Double loop system. Water is transported via a pipeline to the ground water in the same way as a closed system, vertical heat pump but this heat pump type uses groundwater instead of encapsulated water.
Ground-water heat pump	Heat from the underground to heat a central heating system based on water.
- Direct exchange heat pump (DX heat pump)	Heat from the underground is transported using a tube system filled with a fluid to a central heating system based on water (Omer, 2008).

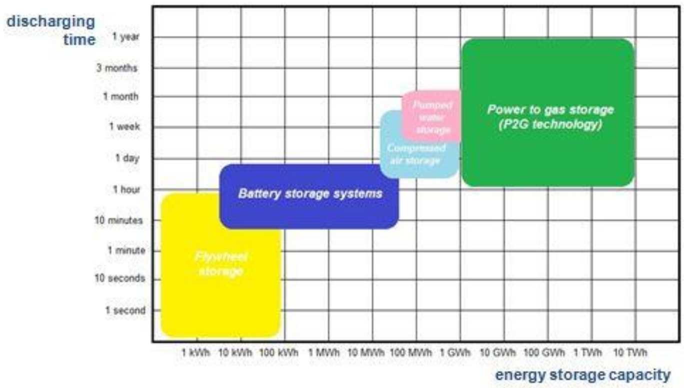
Overview of different heat pumps suitable for space and tap water heating in the built environment.

Geothermal heat

Geothermal heat is in many ways similar to ground source heat pumps, but it is generated at significantly higher depths and makes use of the thermal energy from the earth's core rather than solar energy that is stored within the ground (Barbier, 2002; Lund et al., 2011). In that sense it is fundamentally different from ground-source heat pumps (GSHPs), which are sometimes confusingly called geothermal heat pumps. Geothermal heat is generated by drilling two holes at a very high depth (between 2000 and 3000m in most geological conditions) at a rather large distance from each other that are connected by a pipeline system above the ground, but not underground. At one pipe, water that is led down gets up to the surface as steam spontaneously (due to artesian pressure), where it condenses as water (Barbier, 2002; Dickson & Fanelli, 2013). This water is transported to a heat exchanger that heats water in a pipeline system in the built environment and then back again, where the water goes down again into the earth, to reduce to keep the pressure level equal. The difference between geothermal heat and ground-source heat pumps (which are sometimes confusingly called geothermal heat pumps) is that geothermal heat is thermal energy derived from pressure and heat generated by the original formation of the planet whereas ground-source heat pumps derive their energy from solar energy that is stored in the subsoil. In regions with geological conditions that are very favourable for geothermal heat (particularly regions with high volcanic activity, e.g. Iceland, Indonesia and Chile), geothermal heat can also be used to generate electricity (Dickson & Fanelli, 2013).

Electricity storage systems

Power to hydrogen gas electricity storage as discussed in Section **2.2.3** is one type of electricity storage (Anderson & Leach, 2004). Electricity storage solutions comprise technologies that are able to store excess electricity supply for periods when demand exceeds supply by converting electricity into chemical and kinetic energy (Hadjipaschalis et al., 2009; Yu et al., 2018). The most common technologies are flywheel technology, battery electricity storage systems, compressed air storage and pumped water storage (in the sequence of discharging time/energy capacity applicability (Hadjipaschalis, et al., 2009; De Boer et al., 2014). In order to place hydrogen energy within a wider perspective, an overview of the operational processes behind these technologies behind the alternatives are in terms of energy capacity and discharging times (although it goes far beyond the scope of this study to elaborate on the technical features of all technologies in detail) could be found in the table below. The 'preferred' (the most suitable) electricity storage solution depends on the situational circumstances (Lund & Salgi, 2009; Mathiesen & Lund, 2009; Evans et al., 2012; Luo et al., 2015). The figure illustrates how different types of electricity storage technologies and their respective discharging time/energy volume efficiencies are related.



Different solutions for electricity storage and their technological barriers regarding discharging time and energy capacity (after Dunn et al., 2011; Luo et al., 2015).

Energy storage technology	Operational process	Peak demand duration
Flywheel energy storage (FES)	Flywheel energy storage works by accelerating a rotating flywheel to a very high speed using electric energy. The energy is maintained in the system as rotational energy. When energy demand is higher than supply, the flywheel's rotational speed is reduced and energy is released to the grid. Adding electricity to the system correspondingly results in an increase in the speed of the flywheel. The flywheel and electricity-driven motor are placed in a vacuum to reduce friction with air (Hadjipaschalis et al., 2009; Dincer & Rosen, 2010)	Few seconds to few hours
Battery storage (BESS)	Battery electricity storage systems (BESS) work by charging a rechargeable battery with one or more electrochemical cells when electricity supply exceeds demand. When demand exceeds supply, the electricity is released to the grid like in a conventional battery (Dunn et al., 2011; Li et al., 2013).	10 minutes to 1 day
Compressed air energy storage (CAES)	Compressed air energy storage (CAES) works by using excess electricity supply to compress air into large (underground) reservoirs like defunct mines. Expanding the air generates electricity from the kinetic power that is involved with decompression (Lund & Salgi, 2009; Cleary et al., 2015).	Few hours to few days
Pumped-storage hydroelectricity (PSH)	Pumped-storage hydroelectricity (PSH) works by pumping water from hydropower plants back up again in situations when electricity supply exceeds demand using the excess electricity. The water is let down again in excess-demand situations and the kinetic hydropower energy is then used to power electricity-generating turbines (Deane et al., 2010; Yu et al., 2018).	Few days to few weeks
Power-to-(hydrogen)-gas storage (P2(H)G)	Power-to-hydrogen gas storage (P2(H)G) works by using excess electricity supply to decompose water (H_2O) by electrolysis into hydrogen (H_2) and oxygen (O_2). The hydrogen gas can be stored in gas containers above the ground for short term storage or in large underground reservoirs (salt caverns) for long term storage. When demand exceeds supply, hydrogen gas can be used to feed fuel cells or by hydrogen-powered thermal power plants. (Gregory, 1975; Anderson & Leach, 2004; Lyseng et al., 2017)	F11ew hours to 1 year

Operational processes of different electricity storage technologies.

Appendix 2: Tables on technological specifications of hydrogen

Appendix 2.1: Hydrogen production methods

Hydrogen production method	Efficiency	Maturity	Sustainability
Carbohydrate-based methods			
Steam reforming (SR)	70-85%	Commercial	Not sustainable
Partial oxidation (POX)	60-75%	Commercial	Not sustainable
Autothermal reforming (ATR)	60-75%	Short-term	Not sustainable
Plasma reforming	9-85%	Long-term	Potentially sustainable
Aqueous phase reforming	35-55%	Med.-term	Potentially sustainable
Ammonia reforming	N/A	Short-term	Potentially sustainable
Biomass gasification	35-50%	Commercial	Sustainable
Dark fermentation	60-80%	Long-term	Sustainable
Photo fermentation	0.1%	Long-term	Sustainable
Microbial electrolysis cells	78%	Long-term	Sustainable
Water-based methods			
Photolysis	0.5%	Long-term	Sustainable
Alkaline electrolyser	50-60%	Commercial	Sustainable
PEM electrolyser	55-70%	Short-term	Sustainable
Solid oxide electrolysis cells	40-60%	Med.-term	Sustainable
Thermochemical (TC) water splitting	N/A	Long-term	Sustainable
Photoelectricochemical (PEC) water splitting	12.4%	Long-term	Sustainable

Overview of hydrogen production methods, their operational processes, an indication of efficiency and indication of sustainability in terms of CO_2 emissions (Holladay et al., 2009; Kalamaras & Efstathiou, 2013). Potentially sustainable options are only sustainable if biomass is used. This table is connected to Section ***2.3.1*** *on production.*

Appendix 2.2: Hydrogen storage methods

Storage method	Operational process	Advantages	Disadvantages
Compressed gas storage	Storage under extremely high pressure (>700 bar).	Lightweight, highly beneficial for fuel purpose, occupies smaller space and energy effective.	Requires high pressure cylinder, volumetrically and gravimetrically inefficient.
Cryogenic (liquid) storage	Storage under extremely cold conditions (< 251,5°C).	Volumetrically and gravimetrically efficient, long term hydrogen storage.	Requires compressed tanks, suffers from large energy loss due to liquefaction and boil off process and high tank cost.
Chemical storage	Storage in chemical substances like ammonia, carbohydrates and others, by which hydrogen is generated through chemical reactions.	High storage density and low reactivity and short storage time.	Reacts violently with moist air, cumbersome to handle, absorption of impurities, lack of reversibility, desorption at elevated temperature and slow kinetics of dehydrogenation.
Physical adsorption by porous materials (solid) storage	Storage of gas molecules in porous solid materials under pressure (>100 bar).	Fully reversible process, no accumulation of impurities, fast cycle life and refilling time.	Clustering problem requires low temperature or exceedingly high pressure and shows weak interaction with the H_2 molecule.

Overview of different hydrogen storage methods developed so far, with their respective operational processes, advantages and disadvantages (after Niaz et al., 2015).

Appendix 3: Overview of interview procedures, interview questions and their connection to the conceptual framework

The table below provides an overview of the different interview questions that were asked during the interviews. The table also points out the linkage of the questions to the elements in the conceptual framework (Section **3.6**). It also links these elements and the questions to the sub-questions of this study they are aimed to contribute to.

All interviews were held in Dutch, because all respondents and the researcher have Dutch as their native language. Hence, all the questions are first written down in Dutch and later translated into English. Before the researcher started to ask questions to the respondents, the next steps were followed:

- Introduction (name, study programme, internship);
- Explanation of purpose of research and research objectives;
- Explanation of interview procedures (length, structure, confidentiality);
- Signing of the form of consent **(Appendix 6)**

After that, the questions as shown in the table below were asked according to the type of stakeholder that was interviewed. All interviews were finished with the following remarks:

- Room for the respondent to ask questions that have not been asked and elaborate on subjects that have not been covered;
- General word of thank to the respondent for scheduling time to conduct the interview;
- Question if respondent has recommendations for other respondents;
- Question if respondent has relevant documents on hydrogen energy applications and/or energy transition in the built environment;
- Option to receive the results, a summary and/or the entire study after the study is finished and graded.

After the interview, the recorded interviews were transcribed using InqScribe (a software programme specifically designed for that purpose) and coded according to the coding scheme (**Appendix 5**) in ATLAS.ti. An example of how this coding process is done could be found in the figure below. The interview recordings and transcripts are available on request by sending an email to ***dionglastra@gmail.com***.

Coding example:

Example of a coded passage in the interview transcript, that was set up after the interview with respondent 6 (New Energy Coalition) in ATLAS.ti.

Overview of interview questions and connection to the conceptual framework and sub-questions				
Stakeholder category	**Interview question**	**Translation**	**Link to conceptual framework**	**Sub-questions**
Introduction (same for each respondent)	Wat is uw functie binnen (organisatie) en wat zijn uw verantwoordelijkheden?	What is your function within (organization) and what are your responsibilities?	-	-
	Hoe kijkt u naar het toepassen van waterstof als energiedrager in het algemeen en voor de gebouwde omgeving?	What is your opinion on the application of hydrogen as an energy carrier in general and for the built environment?	Opportunities and challenges	1,3
Academics and research institutes	Welke mogelijke consequenties heeft het implementeren van waterstofenergietoepassingen volgens u voor de huidige invulling van de energievraag en de daarbij horende infrastructuren in de gebouwde omgeving?	What are the possible consequences of the implementation of hydrogen energy applications for the current energy consumption patterns and the corresponding infrastructural networks in the built environment?	Attributes of hydrogen as energy carrier, characteristics of the built environment	1
	Wat is volgens u de huidige stand van zaken ten aanzien van de marktgereedheid van waterstofenergietoepassingen voor de gebouwde omgeving?	What is, according to you, the current situation regarding the market readiness of hydrogen energy applications for the built environment?	Energy transition in the built environment, Market readiness, Opportunities and challenges to incorporation	1,2 3
	Welke rol(len) ziet u weggelegd voor waterstof-energietoepassingen vor de gebouwde omgeving bij de verduurzamingsoperatie voor de gebouwde omgeving?	Which role(s) do you think hydrogen energy applications will have within the energy transition in the built environment?	Attributes of hydrogen as energy carrier, energy transition in the built environment	1, 3
	In welke mate denkt u dat overheden over voldoende kennis en middelen beschikken om de kansen en risico's van verschillende duurzame energie-alternatieven goed te kunnen afwegen? Zijn er daarbij verschillen te merken tussen de verschillende lagen overheden?	To what extent do you think governments have enough knowledge and resources to adequately indicate the opportunities and challenges connected to the different sustainable energy alternatives? Are there, within this regard, differences between the different decentralised authorities?	Decentralisation of energy planning responsibilities	1,3,6
	Wat vindt u van het huidige overheidsbeleid ten aanzien van de verduurzaming van de gebouwde omgeving?	What is your opinion on the current government policy regarding the 'sustainabilisation processes of the built environment?	Opportunities and challenges, Regime level, Landscape level	2,3,6
	Welke instrumenten of maatregelen kunnen overheden volgens u toepassen om waterstofenergietoepassingen te ontwikkelen, op te schalen of te implementeren in het kader van de verduurzaming van de gebouwde omgeving?	Which instruments or measures are, according to you, suitable tools for governments to develop, upscale or incorporate hydrogen energy applications, regarding the desire to 'sustainabilise' the built environment?	Regime level, Reflexive activities, Explorative attitude, Innovative niche development	2,6

	Wat zou volgens u de rol van de netbeheerders moeten zijn in de energietransitie in de gebouwde omgeving, met het oog op waterstoftoepassingen?	According to you, what should be the role of TSOs in the energy transition in the built environment, regarding hydrogen energy applications?	Institutional frameworks, Explorative attitude	4,5,6
	Specific case study-related questions for research institutes			
	Op welke manier bent u betrokken bij het project Nijstad-Oost/Erflanden in Hoogeveen?	In what ways you are involved in the project Nijstad-Oost/Erflanden in the municipality of Hoogeveen?	Regime level	4,5
	Hoe wordt er in dit project omgegaan met de sociale acceptatie van waterstofenergietoepassingen?	How is the social acceptance of hydrogen energy applications for the built environment dealt with in this project?	Willingness and ability of stakeholders and society	3,5,6
Decentralised authorities	Wat is het huidige beleid binnen provincie/gemeente (…) ten aanzien van de energietransitie in de gebouwde omgeving?	What is the current policy within province/municipality (...) regarding the energy transition in the built environment?	Regime level	1,2
	Tegen welke barrières loopt u als provincie/gemeente aan vanuit de Rijksoverheid/de provincie?	What barriers do you face as province/municipality from the national government/the province?	Opportunities and challenges, Regime level, Landscape level	3,5,6
	Hoe houdt de provincie/de gemeente ontwikkelingen op het gebied van de energietransitie in de gebouwde omgeving in de gaten? Welke personen en/of afdelingen zijn hier verantwoordelijk voor?	How does the province/municipality stay updated about developments in the energy transition in the built environment? Which persons or departments are responsible for this?	Innovative niche development, Explorative attitude	4
	Welke rol is er volgens u weggelegd voor waterstofenergietoepassingen in de gebouwde omgeving binnen de transitie?	Which position do you think hydrogen energy applications might fulfil within the energy transition in the built environment?	Attributes of hydrogen as energy carrier, Opportunities and challenges to implementation	1,3
	Welke maatregelen en middelen heeft u beschikbaar om duurzame initiatieven in de gebouwde omgeving te stimuleren en/of te realiseren?	Which tools and measures are available in your province/municipality to stimulate and/or realise sustainable initiatives in the built environment?	Innovative niche development, Explorative attitude	4
	Denkt u dat de provincie/ gemeente over voldoende kennis en middelen beschikt om de transitie naar een duurzame gebouwde omgeving te kunnen uitvoeren? Of denkt u dat daarin de Rijksoverheid/de provincie daarin (ook) een leidende rol zouden moeten hebben?	Do you think the province/municipality has enough knowledge and resources to guide the energy transition in the built environment? Or do you think the national government/the province should (also) have a leading role?	Multilevel governance perspective, Acting space, Decentralisation of energy planning responsibilities	5
	Wat zou er volgens u moeten veranderen om de provincie/gemeente haar rol in de energietransitie in de gebouwde omgeving het beste uit te voeren?	What should, according to you, be changed in order for the province/municipality to optimally perform their roles in the energy transition in the built environment?	Opportunities and challenges to incorporation	3,6
	Hoe gaat de provincie/gemeente om	How does the province/municipality	Involvement of so-	3,5,6

	met het vraagstuk van maatschappelijk draagvlak voor de energietransitie in de gebouwde omgeving?	deal with the issue of social acceptance of the energy transition in the built environment?	ciety	
	Specific case study-related questions for decentralised authorities			
	Wat is uw rol in het project Nijstad-Oost/Erflanden (in Hoogeveen)?	How are you/your organisation involved in the project Nijstad-Oost/Erflanden (in the municipality of Hoogeveen)?	Regime level, legislative and regulatory framework	4,5
	In welk(e) opzicht(en) is de rol van de provincie anders dan die van de gemeente binnen dit project?	To what extent is the role of the province different from the role of the municipality within this project?	Regime level, stakeholder complexity	5
	Hoe gaat de gemeente/provincie binnen dit project om met het aspect van sociale acceptatie van waterstofenergietoepassingen in de gebouwde omgeving?	How does the municipality/province deal with the subject of social acceptance of hydrogen energy applications in the built environment within this project?	Stakeholder complexity, Involvement of society	3,5,6
TSOs	Wat is de rol van Gasunie/TenneT/regionale netbeheerders in de energietransitie in de gebouwde omgeving?	What role does Gasunie/TenneT/regional TSOs have within the energy transition in the built environment?	Regime level, Energy transition in the built environment	4,5
	Welke mogelijke consequenties heeft het implementeren van waterstofenergietoepassingen volgens u voor de huidige invulling van de energievraag en de daarbij horende infrastructuren in de gebouwde omgeving?	What are the possible consequences of the implementation of hydrogen energy applications for the current energy consumption patterns and the corresponding infrastructural networks in the built environment?	Opportunities and challenges; Attributes of hydrogen as energy carrier, characteristics of the built environment	1,3,6
	Welke rol(len) ziet u weggelegd voor waterstofenergietoepassingen vor de gebouwde omgeving bij de verduurzamingsoperatie voor de gebouwde omgeving?	Which role(s) do you think hydrogen energy applications will have within the energy transition in the built environment?	Energy transition in the built environment, Attributes of hydrogen as energy carrier, energy transition in the built environment	1,3
	In welke mate verandert de rol van Gasunie/TenneT/regionale netbeheerders als gevolg van de energietransitie in de gebouwde omgeving?	To what extent is the role of Gasunie/TenneT/regional TSOs subject to change as a consequence of the energy transition in the built environment?	Regime level, path dependency of institutions	4,5
	Wat vindt u van het huidige overheidsbeleid ten aanzien van de verduurzaming van de gebouwde omgeving?	What is your opinion on the current government policy regarding the 'sustainabilisation processes of the built environment?	Regime level, opportunities and challenges	3,5,6
	Hoe ziet u de rol van de Rijksoverheid, provincies en gemeenten in de energietransitie in de gebouwde omgeving?	How do you see the role of the national government, provinces and municipalities in the energy transition in the built environment?	Regime level, Landscape level	5
	Hoe houdt Gasunie/TenneT/RENDO de ontwikkelingen op het gebied van de energietransitie in de gebouwde	How does Gasunie/TenneT/RENDO stay updated about developments in the energy transition in the built en-	Regime level, Explorative attitude, Reflexive activities,	2,4,5

	omgeving in de gaten? Welke personen en/of afdelingen zijn hier verantwoordelijk voor?	vironment? Which persons or departments are responsible for this?	Transition management	
	Wat zou er volgens u moeten veranderen om Gasunie/TenneT/RENDO haar rol in de energietransitie in de gebouwde omgeving het beste uit te voeren?	What should, according to you, be changed in order for Gasunie/TenneT/RENDO to optimally perform their roles in the energy transition in the built environment?	Energy transition in the built environment, Regime level, Legislative and regulatory framework	3,6
	Hoe gaat Gasunie/TenneT/RENDO om met het vraagstuk van maatschappelijk draagvlak voor de energietransitie in de gebouwde omgeving?	How does Gasunie/TenneT/RENDO deal with the issue of social acceptance of the energy transition in the built environment?	Willingness and ability of stakeholders and society	3,4,5
	Specific case study-related questions for TSOs			
	Op welke manier bent u betrokken bij het project Nijstad-Oost/Erflanden in Hoogeveen?	In what ways you are involved in the project Nijstad-Oost/Erflanden in the municipality of Hoogeveen?	Operational activities, innovative niche development	4,5
	Hoe is de samenwerking tussen de betrokken partijen geregeld?	How is the cooperation between the involved parties regulated?	Innovative niche development	4,5
	Wat is volgens u de huidige stand van zaken van het project?	What is, according to you, the current status of the project?	Innovative niche development, operational activities	2
	Is het project voor u (tot dusver) succesvol? Zo ja, wat is voor u het meest succesvolle? Zo nee, waarom niet?	Do you think this pilot (until so far) is successful in achieving its objectives? If so, what is the most successful part of it? If not, why not?	Innovative niche development, reflexive activities, transition management	1,3,6
	Hoe gaat Gasunie/TenneT/RENDO binnen dit project om met het aspect van sociale acceptatie van waterstofenergietoepassingen in de gebouwde omgeving?	How does Gasunie/TenneT/RENDO deal with the subject of social acceptance of hydrogen energy applications in the built environment within this project?	Willingness and ability of stakeholders and society	3,5,6
Niche actors (HYDORGRE ENN)	Welke kansen en uitdagingen ziet u voor waterstofenergietoepassingen in de energietransitie voor de gebouwde omgeving?	Which opportunities do hydrogen energy applications have within the energy transition in the built environment, according to you?	Opportunities and challenges	1,3,6
	Hoe denkt u over het aspect van maatschappelijk draagvlak van waterstofenergietoepassingen in de gebouwde omgeving?	What opinion do you have on the issue of social acceptance of hydrogen energy applications for the built environment?	Opportunities and challenges	3,5,6
	Wat vind u van het beleid van overheden met betrekking tot de energietransitie in de gebouwde omgeving en de houding ten aanzien van waterstofenergietoepassingen daarbinnen?	What is your opinion on government policies regarding the energy transition in the built environment and the attitude regarding hydrogen energy applications therein?	Energy transition in the built environment; Opportunities and challenges; Transition management	2,3,6
	Wat zou er volgens u moeten veranderen om waterstofenergietoepassingen in de gebouwde omgeving te faciliteren?	What should, according to you, change in order to facilitate hydrogen energy applications in the built environment?	Energy transition in the built environment; Opportunities and challenges; Innovative niche	3.6

			development	
	Hoe is HYDORGREENN als waterstofcoalitie ontstaan?	How did HYDORGREENN emerge as a hydrogen coalition?	Innovative niche development	1,2,4,5
	Welke soorten partijen zijn aangesloten bij HYDORGREENN?	What types of actors are affiliated with HYDORGREENN?	Willingness and ability of stakeholders and society	5
	Wat zijn de belangrijkste doelstellingen van HYDORGREENN?	What are the main goals HYDORGREENN wants to achieve?	Energy transition in the built environment, operational activities, reflexive activities	1,2,3
	Op welke wijze en met wie werkt HYDORGREENN samen om deze doelstellingen te bereiken?	How and with whom does HYDORGREENN collaborate to achieve these goals?	Operational activities, reflexive activities	4,5
	Specific case study-related questions for the niche level actors			
	Hoe kwam binnen HYDORGREENN het idee om Nijstad-Oost/Erflanden als pilotproject voor waterstofenergietoepassingen in de gebouwde omgeving?	How did the idea arise within HYDORGREENN to use Nijstad-Oost/Erflanden as a pilot project for hydrogen energy applications in the built environment?	Innovative niche development, Explorative attitude	1,2,4,5
	Hoe is dit initiatief aanhangig gemaakt bij de verantwoordelijke overheden en wie onderhoudt daarover het contact?	How did this initiative reach the responsible authorities and who is responsible for maintaining contacts with these authorities?	Operational activities, Explorative attitude	4,5
	Hoe is de samenwerking tussen de betrokken partijen geregeld?	How is the cooperation between the involved parties regulated?	Innovative niche development	4,5
	Wat is volgens u de huidige stand van zaken van het project?	What is, according to you, the current status of the project?	Innovative niche development, operational activities	2
	Is het project voor u (tot dusver) succesvol? Zo ja, wat is voor u het meest succesvolle? Zo nee, waarom niet?	Do you think this pilot (until so far) is successful in achieving its objectives? If so, what is the most successful part of it? If not, why not?	Innovative niche development, reflexive activities, transition management	1,3,6

Appendix 4: Example of document analysis

The illustration below shows a marking in a policy document that has been analysed. The marked pdf-documents are available on request by sending an e-mail to ***dionglastra@gmail.com.***

industrie. Meer recent wordt gewerkt aan de toepassing van waterstof als transportbrandstof. Hiermee kunnen voertuigen, treinen, mobiele werktuigen en waarschijnlijk ook vaartuigen volledig elektrisch worden, in combinatie met brandstofcellen. Waterstof kan onder druk in vloeibare vorm compact worden opgeslagen voor diverse toepassingen. Op termijn zou waterstof de rol van aardgas kunnen vervangen bij lage temperatuur ruimteverwarming in huizen en gebouwen. Verder kan waterstof grote waarde hebben bij de opslag van elektriciteit en bij het energietransport van offshore windparken naar land. Waterstof is relatief eenvoudig te transporteren en te bufferen in pijpleidingen en op te slaan in tanks. Het kan dan ook op termijn een belangrijke rol spelen bij versterking van de flexibiliteit van het elektriciteitssysteem (opslag en CO_2-vrij regelbaar vermogen).

A marked passage in Voorstel voor Hoofdlijnen van een Klimaatakkoord (SER, 2018), in which the possible future role of hydrogen energy applications in the built environment is highlighted.

Appendix 5: Coding scheme for semi-structured interviews

Sustainable innovative niche

- Bottom-up developments
- Pilots and experiments
- Operational activities

Energy transition in the built environment

- Current energy supply system
- Landscape level strategic activities
- Regime level tactical activities
- Transition multiphase perspective
- Transition multilevel perspective

Opportunities and challenges

- Energy demand characteristics of the built environment

- Attributes of hydrogen
- Feasibility of alternatives
- Market readiness and investment costs
- Complexity of governance
- Uncertainty
- Path dependency of institutions
- Willingness and ability of stakeholders and society
- Legislative and regulatory frameworks
- Decentralisation in energy planning responsibilities

Roles of stakeholders
- Role of municipality
- Role of province
- Role of national government
- Role of EU
- Role of market stakeholders
- Role of research institutes
- Role of TSOs
- Role of society

Transition management activities
- Explorative attitude
- Exploitative attitude
- Reflexive activities

SWOT
- Strength
- Weakness
- Opportunity
- Threat

Appendix 6: Form of consent for semi-structured interviews

Toestemmingsformulier interview
Faciliteren van waterstofenergie in de gebouwde omgeving

Doel van het onderzoek
In kaart brengen van de planologische en organisatorische uitdagingen die komen kijken bij het toepassen van waterstof als energiedrager in de gebouwde omgeving voor zowel warmte- als elektriciteitstoepassingen. Aan de hand daarvan wordt geprobeerd aanbevelingen te doen voor concrete stappen die de implementatie van waterstof in de gebouwde omgeving kunnen vergemakkelijken.

Wat wordt er van u gevraagd?
U hoeft zich niet voor te bereiden op het gesprek. Dit interview wordt gehouden vanwege mijn interesse naar uw (werk)ervaring met waterstofenergie en/of de verduurzaming van de gebouwde omgeving i.h.k. van de energietransite. De meeste interviews duren gemiddeld ongeveer *één uur*, maar korter of langer kan natuurlijk ook. U kunt tijdens het gesprek altijd aangeven als u wilt stoppen of even pauze wilt nemen. Ook kunt u het aangeven wanneer u een vraag niet wilt beantwoorden, wat uiteraard gerespecteerd wordt

Wat gebeurt er met uw gegevens?

- Het gesprek mag worden opgenomen: JA / NEE

  Indien het gesprek wordt opgenomen, zal de opname met zorg bewaard worden en worden opgeslagen in een beschermde omgeving. Alleen de onderzoeker en de begeleiders van de onderzoeker zullen toegang hebben tot het gesprek. De geluidsopname en de inhoud van het gesprek zullen alleen voor dit onderzoek worden gebruikt.

- Indien gewenst kunt u ervoor kiezen niet uw werkelijke naam te gebruiken voor dit onderzoek. In dat geval worden (al dan niet gefingeerde) initialen of een pseudoniem gebruikt in de uitwerking. Uw identiteit wordt uiterst vertrouwelijk behandeld en is strikt geheim voor iedereen, met uitzondering van de onderzoeker en de begeleiders.

- De resultaten zullen worden verwerkt in een wetenschappelijke masterthesis. Deze thesis heeft de vorm van een papieren rapport en over dit papieren rapport wordt een presentatie gehouden tijdens de Graduate Research Day van de faculteit Ruimtelijke Wetenschappen van de Rijksuniversiteit Groningen in januari 2019. Deze presentatie is toegankelijk voor publiek, dat voornamelijk zal bestaan uit medestudenten, universitair docenten en andere belangstellenden.

- Indien u dat wenst kunt u na afronding van het onderzoek een kopie van het onderzoek toegestuurd krijgen.

Toestemming
Bij deze verklaar ik dat ik op de hoogte ben gesteld van:
1. het doel van het onderzoek;
2. wat er van mij verwacht wordt tijdens en na het gesprek;
3. en wat er met mijn gegevens gebeurt.

Datum: ___________________ Handtekening deelnemer: ______________________

Datum: ___________________ Handtekening onderzoeker: ______________________

Alss u verdere vragen en opmerkingen heeft, dan kunt u te allen tijde contact op nemen.
Onderzoeker: Dion (D.Y.) Glastra, BSc. (e-mail: dion.glastra@rhdhv.com)
Begeleider: dr. Ferry (F.M.G.) Van Kann (e-mail: f.m.g.van.kann@rug.nl)

The signed forms of consent are available on request by sending an email to dionglastra@gmail.com

Appendix 7: Overview of stakeholders involved in the case study

The table below provides an overview of all stakeholders that are formally involved in the case study of Nijstad-Oost/Erflanden in Hoogeveen **(Chapter 5).** Roles of stakeholders that are relevant to mention with regard to the study, are added to the overview.

Stakeholder	Role *(if relevant)*
Alliander	
Bekaert B.V.	Signer of first subsidy request H_2oogeveen
DNV-GL	
GasTerra	Signer of first subsidy request H_2oogeveen
Gasunie Transport Services*	Signer of first subsidy request H_2oogeveen
Gemeente Hoogeveen*	***Municipality in which the planned development is situated;*** Signer of first subsidy request H_2oogeveen
Green Planet	
Groningen Seaports	

Holthausen	
JP-Energiesystemen	Signer of first subsidy request H_2oogeveen
Kiwa	
NAM	Signer of first subsidy request H_2oogeveen
Nedstack	Signer of first subsidy request H_2oogeveen
New Energy Coalition*	***Source of practical and theoretical knowledge, research institute;*** Signer of first subsidy request H_2oogeveen
Provincie Drenthe*	***Initial proposer of the idea to use hydrogen energy applications;*** Signer of first subsidy request H_2oogeveen
RENDO / N-TRA*	***Local TSO for gas distribution*** Signer of first subsidy request H_2oogeveen
Royal HaskoningDHV**	***Internship company /*** advising RENDO/N-TRA on concept plan for hydrogen-based energy infrastructure
Samenwerkende Bedrijven Eemsdelta	
Siemens	Signer of first subsidy request H_2oogeveen
STORK*	***Employer of the chairman of HYDORGREENN, project leader of case study;*** Signer of first subsidy request H_2oogeveen
Tieluk	
TNO	
Veiligheidsregio Drenthe	
Visser & Smit Hanab	

*: Stakeholder interviewed with particular focus on the case study.
**: Internship company