

# The challenges of integrating hydrogen in the Dutch natural gas infrastructure

A socio-technical analysis on the challenges of integrating hydrogen in the Dutch gas infrastructure for the provision of gas to the built environment



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A socio-technical analysis on the challenges of integrating hydrogen in the Dutch gas infrastructure for the provision of gas to the built environment

By

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## Preface

This thesis is about the use of hydrogen gas as an alternative to natural gas in the satisfaction of the heat demand of our houses and buildings. Hydrogen gas seems relevant as a solution to substitute natural gas in the built environment and hence in the decarbonization of our gas supply. The question is however, if the current natural gas infrastructure is suitable for a provision of hydrogen to the Dutch residential and service sector. The thesis project is conducted on behalf of Delft University of Technology and concludes my journey here.

The replacement of natural gas in the energy provision to the Dutch built environment is an enormous challenge. This challenge implies serious opportunities for the redesign of our energy systems and hence for the design of our future energy systems. The implications of the integration of alternatives to natural gas on the way in which we can decarbonize our energy systems interest me. Especially looking at the way in which our current economic conception on the functioning of energy systems can be broadened. Inspired by my graduation committee and by the enthusiasm that I recognized in society, I decided to put my focus on the replacement of natural gas by hydrogen gas.

Conducting my thesis project was an instructive and eventually a satisfying process. I especially want to thank Daniel Scholten, my first supervisor, for his contribution to my graduation. Daniel was always available to help me out with his support and feedback. Especially his experience as an academic and his critical but open view on the academic theory helped me a lot. I really appreciated our collaboration and his effort. I also want to thank Gijsbert Korevaar, my second supervisor, for his help with the more technical content of my thesis subject. Furthermore, I want to thank Rolf Künneke, the chair of the committee, for his critical view and his direction in the scope of my thesis project. All of you were very helpful and motivating.

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Stijn Jonathan Bekkers  
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## Executive summary

The Dutch climate policy regarding the residential sector and the service sector states that all buildings need to be provided by an alternative to natural gas in the provision of heat by 2050. The heat provision to the residential and service sector is currently for more than ninety percent based on the local combustion of natural gas. The natural gas infrastructure will no longer be needed for the provision of energy to the residential and service sector when the natural gas connections of these buildings are replaced by other alternatives than gas, such as all-electric or district heating. The latter implies that the comprehensive and costly natural gas infrastructure will not be used anymore and a large gap in the provision of energy to the residential and service sector will arise. Hydrogen gas can be used as a sustainable alternative to natural gas in the existing infrastructure to fill in this gap and safeguard the existence of our energy transport and buffer capacity. The latter implies that hydrogen gas needs to be produced, transported, stored, and consumed within the operational and market constraints of the existing natural gas infrastructure. The following research question is formulated:

*How to successfully integrate hydrogen into the current natural gas infrastructure and guarantee the adequate provision of energy to the Dutch residential and service sector?*

The relationship between institutions and technology in the design practices regarding energy infrastructures is often not adequately addressed. Economists, legal experts, and policy makers focus on market designs and engineers focus on the design of the technical systems. The fragmentation in the execution of these distinctive design practices can be problematic when design choices of economists, legal experts, and policy makers are not considering the design choices of engineers (and vice versa). The latter can be troublesome when the natural gas infrastructure is redesigned to provide hydrogen. To investigate how hydrogen gas can be integrated successfully in the current natural gas infrastructure, it is hence important to include the gas market, the physical gas infrastructure, and their interrelation in the conceptualization of the natural gas infrastructure.

The comprehensive design framework is consulted to adequately conceptualize the Dutch gas infrastructure within the notion of a more integrated technical and market design. This framework provides the basis for the taken research approach and allows for a structured analysis on the implications of a successful integration of hydrogen into the Dutch natural gas infrastructure within the concepts of socio-technical systems. Expert interviews were conducted to collect the data about the design challenges of a hydrogen provision through the existing gas infrastructure. The integration of hydrogen in the thesis project is investigated based on the integration of both centralized and decentralized hydrogen production and storage technologies.

The current natural gas infrastructure design is based on a natural gas supply that is centrally produced and stored. Gas is produced from natural gas fields and transported in a top-down fashion through the public grids to the end-users. The technical operation and the gas quality of the public pipeline networks are strictly regulated by the public system operators. The market function is based on the open-access principle of these public grids. The wholesale market allows licensed parties to openly transact bulk gas that is transported through the public transmission grid. The retail market allows small-scale end-users to buy gas competitively based on the ability of the licensed retail suppliers to buy gas strategically in the wholesale market. The retail gas is distributed through the public distribution grids. Public system operators are obliged to connect every party that is willing to in the predefined constraints of the grid.

The existing design and operations of the natural gas infrastructure needs to change when hydrogen is integrated. A new hydrogen gas production and storage segment will need to be added and new hydrogen gas standards will need to be formulated. A hydrogen gas market needs to be established to facilitate the hydrogen transactions and the current gas laws and regulations will need to be reformulated. These new system elements need to be integrated within an existing and well-functioning gas infrastructure. The new gas production and storage segments, in combination with the need to establish a hydrogen market hence pose challenges to the adequate provision of energy to the Dutch residential and service sector. When hydrogen is replacing natural gas in the existing infrastructure, enough hydrogen supply and demand needs to emerge timely to match the functioning of the natural gas system. The Gas Act, the Mining Act, and the energy codes prohibit the provision of hydrogen through the public grids. The gas laws and regulations need to be reformulated to allow for the production, transportation, storage, and consumption of hydrogen. The natural gas grid will need to be transformed gradually to simultaneously address the security of supply and the organizational challenges of transforming the grid and installing the production technologies and end-use equipment. The decentral supply of hydrogen gas will make the adjustments to the natural gas grid and the gas market model more intensive. The centralized supply of hydrogen gas is more in line with the current provision of gas and hence includes the path of the least resistance.

The comprehensive design framework has proven to be an adequate tool in bridging the gap between engineers and economists, legal experts, and policy makers. The framework especially functions as a tool to strive for the completeness in the conceptualization of energy infrastructures. The framework therewith mainly allows for the identification of design challenges that exists in between the institutions and the technology. The individual design perspectives provide much more detailed knowledge and stay relevant in the deeper understanding of our energy systems. The comprehensive design framework aids in the linkage of the individual design perspectives and the prevention of perverse effects from the neglect of the linkage.

The integration of hydrogen will unavoidably be dependent on the regulatory intervention in certain design choices. Crucial choices include choices on: the gas quality standards of the public grids, the use of natural gas in relation to the allowance to emit CO<sub>2</sub> and the use of CCS, the dependency on natural gas, the degree to which the system operators can integrate the electricity and gas distribution activities, and the market model in relation to the (inter)national energy markets. Hydrogen can successfully be integrated when the current gas laws- and regulations are adjusted, the energy markets accurately reflect the costs of CO<sub>2</sub>, and hydrogen gas is adopted as the gas standard for the Dutch gas distribution grids. A transition to hydrogen is hence technically possible but requires enormous up-front investments and a clear direction in the future of the Dutch gas infrastructure. The current regulatory and market model do not properly fit the integration of hydrogen. New hydrogen technologies require a new perspective on how to provide energy to the residential and service sector.



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# 1. Introduction

## 1.1 The phase out of natural gas combustion in Dutch buildings

The Dutch government has announced that 7 million houses and 1 million buildings in the service sector need to be provided by sustainable heat in 2050 (Klimaatberaad, 2018b). This is an enormous challenge considering that over 90 percent of the houses and service sector buildings in the Netherlands are currently heated by the local combustion of natural gas (Hans Ariëns, 2018). The objective of this policy measure is in line with the European climate targets to mitigate the effect of climate change (Klimaatberaad, 2018a). Moreover, it helps to facilitate the Dutch policy to stop the natural gas extraction from the largest natural gas field in the Netherlands (Klimaatberaad, 2018a).

To achieve the enormous objective in 2050, the Dutch government is choosing a gradual approach and formulated a first clear policy target for 2030. The CO<sub>2</sub> emissions of the buildings induced by space heating and domestic water heating need to be reduced by 3,4 Mt compared to the 1990 levels (Klimaatberaad, 2018a). Sustainability measures in the service sector should lead to a reduction of 1 Mt and phasing out natural gas in 1.5 million houses in combination with insulation measures should cover the remainder of 2 Mt (Klimaatberaad, 2018a). To adequately meet the demand for space heating and domestic water heating in 2030 and beyond, alternative heating technologies need to be integrated in the energy infrastructures to provide the desired energy demand to the buildings.

Natural gas is currently distributed by means of an extensive gas infrastructure. There is a potential to use the existing infrastructure to distribute and store sustainable gasses such as biomethane or hydrogen (Dodds & McDowall, 2013). Alternative energy infrastructures can also replace the natural gas infrastructure in the satisfaction of the energy demand. Possibilities are the electricity infrastructure and a district heating infrastructure. Energy can also be produced locally from renewable energy sources as biomass, geothermal energy, solar energy, and wind energy.

Since it would be a waste to throw away the extensive and costly natural gas infrastructure, the possibilities for the continuation of its use need to be investigated. Hence, sustainable gasses need to be considered. These gasses need to fit within the policy targets set by the Dutch government. Biomethane (i.e. green gas) is a renewable energy source produced from biomass which can directly replace natural gas in the existing infrastructure since it has a similar composition. The CO<sub>2</sub> emitted at the combustion of biomethane is sequestered with the regrow of the biomass. A large deployment of biomethane would mean that enormous amounts of biomass are needed. This can be problematic in relation to the production of food, the use of land, the production of biomaterials, and the degradation of land used for the production of biomass (Hoogwijk et al., 2003). Moreover, the CO<sub>2</sub> used for the production and transport of the biomass is not sequestered by the regrow of the biomass.

The advantage of the use of hydrogen over hydrocarbon gasses, such as natural gas and biomethane, is that the product of hydrogen combustion consists of water and does not include any carbon emissions. This makes hydrogen an interesting option to replace natural gas. The use of hydrogen as a replacement for natural gas in the existing natural gas infrastructure has some issues regarding its safety, the existing regulations, the use of the conventional compression and metering stations, and the storage and transportation capacities that can be reached (van den Noort, Sloterdijk, & Vos, 2017). Besides, the production of hydrogen has some uncertainties in terms of its costs and environmental benefits (Armaroli & Balzani, 2011). Despite the issues and uncertainties, hydrogen has the potential to be safely integrated within the current natural gas infrastructure (Dodds & Demoullin, 2013). Moreover, from a

cost-optimal perspective, hydrogen might be the only long-term gas decarbonization option that can secure a reliable provision of energy to the buildings (Dodds & McDowall, 2013). Hydrogen can hence play a key role in securing a future application for the extensive natural gas infrastructure in the Netherlands. Moreover, hydrogen has the potential to be a sustainable alternative to natural gas for heating the Dutch buildings (van Wijk & Hellinga, 2018).

When Hydrogen is (partly) integrated in the natural gas infrastructure, a variety of adjustments need to be made to make the natural gas infrastructure compatible with the use of hydrogen. The technical design and operation of the gas infrastructure need to change according to the technical requirements that the use of hydrogen includes. The governance of the gas infrastructure should change accordingly, and proper coordination mechanisms should restrain and enable the actors active within the infrastructure to guarantee a reliable provision of energy.

If the Netherlands is replacing natural gas by hydrogen in the existing gas infrastructure, insights are needed in the possible effects on the reliable provision of energy to the Dutch buildings. That is, insights in the potential problems that an integration of hydrogen can cause for the reliable functioning of the gas infrastructure. Understanding is needed in the way that the current infrastructure design, operation, organization, and coordination need to change to successfully integrate hydrogen. The impact of different possibilities of hydrogen configurations on the reliable functioning of the gas infrastructure needs to be discovered to identify possible hydrogen futures for the Netherlands.

### **1.1.1 Complementarity in the design of the gas infrastructure**

Energy infrastructures, such as the natural gas infrastructure, “comprise all the sources, technologies, actors and institutions involved in the production, transportation, consumption and management of energy.” (Scholten & Künneke, 2016, p. 3) They are conceived to be complex socio-technical systems that exhibit technical and social complexity (Bruijn & Herder, 2009; Chappin & van der Lei, 2014; Herder, Bouwmans, Dijkema, Stikkelman, & Weijnen, 2008; Ottens, Franssen, Kroes, & Van De Poel, 2006; Van der Lei, Bekebrede, & Nikolic, 2010). The technical elements of the natural gas infrastructure consist of the physical assets and the operational activities of managing the physical flow of energy through the supply chain (Scholten & Künneke, 2016). The social elements consist of the actors and the way in which their behavior is regulated in the use of the infrastructure and their related market activities (Chappin & van der Lei, 2014). A socio-technical systems approach to energy infrastructures includes the need for the technical and social elements to be jointly optimized (Bauer & Herder, 2009). The natural gas infrastructure is a complex socio-technical system with a variety of important technologies and social-economic elements (i.e. actors and regulations) that need to function together.

The integration of hydrogen within the Dutch natural gas infrastructure will introduce hydrogen gas production, transportation, and consumption technologies. These technologies will imply different requirements for the technical design and operation of the gas system, and therewith for the overall complementarity of the system elements. The concept of complementarity in the thesis refers to the notion that the design of a specific element of the infrastructure can obstruct the functioning of another element. The different system elements therewith need to be designed to function in a consistent fashion. The current natural gas infrastructure includes an extensive set of institutions that fits the use of natural gas as an energy carrier. Institutions refer here to “the rules of the game in a society or, more formally, the humanly devised constraints that shape human interaction.” (North, 1990, p. 3) The set of institutions ensures that the actors within the infrastructure are well-organized and well-coordinated, and that their activities fit within the technical requirements of the system. By replacing natural gas with hydrogen, uncertainties arise about the complementarity of the institutions with the hydrogen technologies.

Scholten & Künneke (2016) argue that the current way of energy infrastructure design can be problematic for the integration of renewable energy technologies (i.e. sustainable heat technologies). Engineers focus merely on the design of infrastructure assets, network topologies, and control systems that need to function reliably and robustly (Scholten & Künneke, 2016). Economists, policy makers, and legal experts focus on market designs that need to address “potential market failures and imperfections, opportunistic behavior, and social objectives” (Scholten & Künneke, 2016, p. 1). As a result of this fragmentation, neither of the design practices specifically considers the needed complementarity between both dimensions of the design of energy infrastructures (Scholten & Künneke, 2016). This can be problematic for the integration of hydrogen since the different design dimensions can generate conflicting outcomes and result in the malfunctioning of the infrastructure (Scholten & Künneke, 2016). Moreover, this fragmentation makes it unclear what design choices in one dimension imply for the other (Scholten & Künneke, 2016). The latter can result in unexpected or unwanted outcomes that can hamper the reliable provision of gas to the Dutch buildings. Scholten & Künneke (2016) propose a more comprehensive approach of analyzing energy infrastructures to bridge the gap between the engineering and economic perspectives of energy infrastructure design. The basic idea of this approach is that the design variables of the technical and market design need to be filled in a consistent fashion (Scholten & Künneke, 2016). The degree to which these designs are filled in a consistent fashion refers to the degree of alignment between the technology and institutions.

In analyzing the integration of hydrogen in the Dutch natural gas infrastructure, it is important to assess its impact on the functioning of the total system design (i.e. its comprehensive design). The natural gas infrastructure needs to be conceptualized including its technical system design, its market design, and the possible interaction between those designs. If hydrogen is expected to replace natural gas successfully, knowledge is required about the possible effects on the complementarity of the social and technical elements in the Dutch natural gas infrastructure.

### **1.1.2 Problem statement**

The fragmentation in the conceptualization of energy infrastructures can cause problems for the successful integration of hydrogen. It is unclear if the current institutions and technologies of the Dutch natural gas infrastructure match with the use of hydrogen as an energy carrier. Moreover, it is therewith unclear if the integration of hydrogen in the Dutch natural gas infrastructure might cause problems for a reliable provision of gas to the Dutch buildings. The integration of different hydrogen infrastructure configurations might trigger problems for the functioning of the natural gas infrastructure. It is hence unclear what hydrogen infrastructure configurations are feasible within the current institutional boundaries of the natural gas infrastructure and vice versa. The problem statement of the research project is defined as follows:

*It is unclear what the requirements and implications are for the comprehensive design of the Dutch natural gas infrastructure when hydrogen replaces natural gas in the provision of gas to the residential and service sector.*

## **1.2 Research objective**

The research has the objective to obtain insights about the impact of the integration of two hydrogen infrastructure configurations on the functioning of the natural gas infrastructure. One based on the centralized production of hydrogen and one more based on the decentralized production of hydrogen. In researching the impact of the two hydrogen configurations, an attempt is made to contribute to the



knowledge that is necessary to successfully replace natural gas by hydrogen in the energy supply to the Dutch built environment. Insights in the impact of the two hydrogen infrastructure configurations will help to describe the challenges that the integration of hydrogen can cause for the functioning of the Dutch natural gas infrastructure. Moreover, the results of the research can contribute to the knowledge about potential hydrogen infrastructure configurations that can satisfy the residential and service sector heat demand. An attempt is hence made to contribute to the insights of the design of a future gas infrastructure that does not rely on the local combustion of natural gas within the Dutch buildings. The main objective of the research is formulated as follows: *To identify and address the challenges that the integration of hydrogen in the Dutch natural gas infrastructure can cause for the provision of heat to the Dutch residential and service sector.*

To address the stated research objective, the main research question is defined as follows: *How to successfully integrate hydrogen into the current natural gas infrastructure and guarantee the adequate provision of energy to the Dutch residential and service sector?*

To answer the main research question and address the research problem and objective, the sub research questions are formulated as follows:

1. How can the Dutch natural gas infrastructure be conceptualized in terms of the concepts of socio-technical systems?
2. How are the technical system and the market of the Dutch natural gas infrastructure designed and what does this mean for the complementarity within the socio-technical system?
3. What hydrogen infrastructure configurations are feasible to replace natural gas in the Dutch natural gas infrastructure for the heat provision of the residential and service sector?
4. What implications do the integration of the hydrogen configurations have on the functioning of the natural gas infrastructure?
5. What are convenient alterations in the design of the natural gas infrastructure to deal with the implications of the integration of the hydrogen infrastructure configurations?

### **1.2.1 Scope of the research**

The focus of the research is on the techno-operational and economic-institutional implications that an integration of hydrogen can cause for the functioning of the Dutch gas infrastructure. The functioning of the infrastructure refers here to a reliable and robust provision of gas to the residential and service sector. The focus of the research is therewith mainly on the challenges of an integration of hydrogen for the functioning of the gas provision. A specific assessment on the costs and environmental performance of the hydrogen infrastructure is excluded from the scope. The research will focus on the replacement of parts of the natural gas infrastructure by a 100 percent hydrogen infrastructure. The admixture of hydrogen with natural gas is hence not part of the scope.

### **1.2.2 Scientific and social relevance**

The research conducted in the thesis project can be relevant for both scientific and social purposes. Scientifically, the research contributes to the literature on the socio-technical systems design of energy infrastructures. Relevant insights can be gained in the literature on coherence and alignment between technology and institutions in energy infrastructures. These insights can contribute to the understanding about how to better attune the system and market design of the natural gas infrastructure and to the understanding about the further conceptualization of the interrelationship between the techno-operational and economic-institutional dimensions of energy infrastructures. Moreover, by applying the

comprehensive design framework of Scholten & Künneke (2016), a contribution is made to the knowledge about the application and validity of the framework.

Socially, the research can be relevant for engineers, policy makers, legal experts, and economists who face the task to replace natural gas. The research can aid in seeing the broader implications of replacing natural gas in the Dutch residential and service sector. With respect to the design of a future gas infrastructure, the research might help to identify the institutional and technical implications of replacing natural gas by hydrogen. Moreover, it might contribute to the discussion on the convenience of hydrogen to replace natural gas in the heat provision to the Dutch residential and service sector.

### 1.3 Research approach

The research approach that is taken in the thesis project is mainly based on the application of the comprehensive design framework of Scholten & Künneke (2016). Paragraph 1.3.1 elaborates on the comprehensive design framework and the research approach. Paragraph 1.3.2 discusses how the sub research questions are addressed and mentions which research methods apply to the questions. Paragraph 1.3.3 elaborates on the application, limitations, and drawbacks of the chosen research methods.

#### 1.3.1 The comprehensive design framework

The purpose of the comprehensive design framework is defined by Scholten & Künneke (2016, p. 16) as the process of “attuning system and market design efforts so that we may better identify, interpret, and address, the interrelated operational and market challenges to energy infrastructure performance.” The application of the framework is based on its ability to investigate the implications of a techno-operational or economic-institutional change in a structured manner (Scholten & Künneke, 2016). The framework provides a tool for the positioning of these implications in an easy to use comprehensive overview (Scholten & Künneke, 2016), as illustrated in Figure 1.

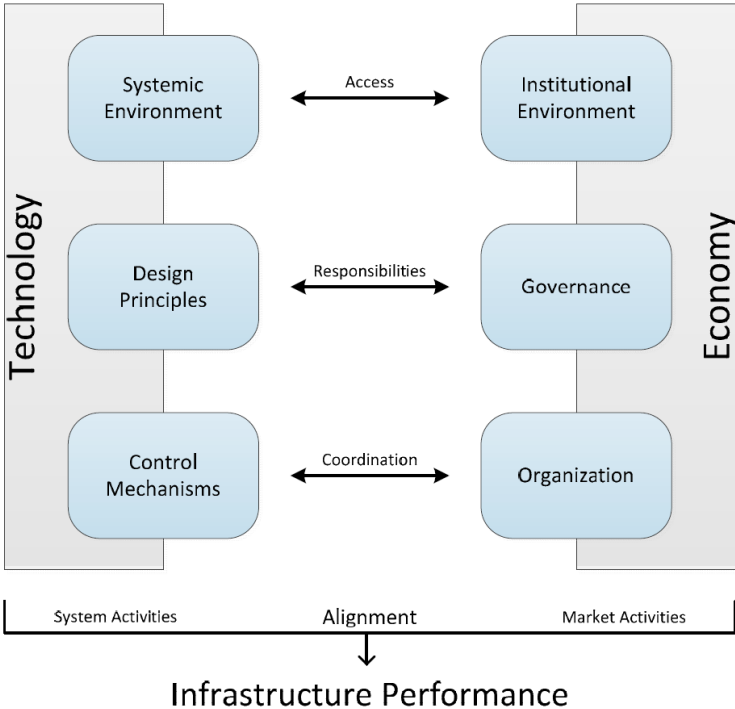


Figure 1: Comprehensive design framework, adopted from Scholten & Künneke (2016, p. 14)

An integration of hydrogen in this thesis project, considers the notion of system integration as “The process of jointly shaping the technical and institutional sub-systems” (Verzijlbergh, De Vries, Dijkema, & Herder, 2014, p. 2). When a system of hydrogen technologies and institutions is integrated in the natural gas infrastructure, it needs to function within the total system. The sub-systems (i.e. technical, social and economic elements) of the natural gas infrastructure need to function together to ensure the reliable operation of the infrastructure. The integration of hydrogen in this thesis project hence refers to the act of integrating hydrogen in the natural gas infrastructure, and to the process of adapting the existing technical and institutional sub-systems for that purpose. The comprehensive design framework provides the means to research the integration of hydrogen in the scope of the thesis.

The research approach consists of several steps that need to be taken to answer the main research question. As a starting point, the current design of the Dutch natural gas infrastructure needs to be captured in an adequate conceptualization. A comprehensive design in this thesis refers to a representation of the natural gas infrastructure that includes both the important technical and market design variables, and the interrelation between them. Hence, the important technical, social, and economic variables of energy infrastructure design and the relation between these variables need to be included in the conceptualization of the natural gas infrastructure. The comprehensive design framework of Scholten & Künneke (2016) is obtained for this purpose. The framework allows for a description within the concept of energy infrastructures as socio-technical systems. Besides the description, the framework functions as a tool to link the different technical, social, and economic design variables of the natural gas infrastructure. The latter function of the theoretical framework is essential in analyzing the consequences of the integration of hydrogen on the functioning of the design variables in the natural gas infrastructure.

To analyze the impact of the integration of hydrogen on the functioning of the natural gas infrastructure, it is necessary to clearly map the current natural gas infrastructure design. The technical and market design of the infrastructure will be described in detail within the specifications of the comprehensive design framework. The description will allow for a structured analysis towards the changes that an integration of a hydrogen poses to a specific variable in the technical or the market design of the natural gas infrastructure. To get insights in potential implications that the gap between the engineering and market design practices might have on the functioning of the natural gas infrastructure, an assessment will be made of the alignment between the technical and market designs.

Hydrogen technologies can be integrated in the natural gas infrastructure in several ways. Different variations and combinations of production, transportation, and consumption technologies are possible. To analyze the impact of the integration of hydrogen on the functioning of the natural gas infrastructure, it is necessary to formulate feasible hydrogen configurations to replace natural gas. These hydrogen configurations will be identified, inspired by existing hydrogen applications or plans to apply hydrogen for the purpose of heating the residential and service sector. The hydrogen infrastructure configurations will function as the input for the analysis towards their potential problems and challenges for the adequate provision of heat to the Dutch residential and service sector.

The output of the previous step is used to assess the potential problems and challenges of an integration of hydrogen in the Dutch natural gas infrastructure. The different hydrogen infrastructure configurations will be assessed separately in terms of the problems that they might imply for the design of the gas infrastructure. An analysis will be conducted on how the design variables in the natural gas infrastructure change under an integration of hydrogen. This will result in an overview of the changes that a specific hydrogen configuration poses on the technical and market design of the natural gas infrastructure. The

indirect effect of the changing design variables on other design variables in the technical and the market design will be analyzed by means of the interrelations defined in the comprehensive design framework. The latter analysis helps to identify the possible implications of the integration of hydrogen for the overall system functioning.

To find viable options for hydrogen configurations, it is necessary to analyze how the identified implications can be mitigated by the alteration of the design variables in the current design of the natural gas infrastructure. The interrelations between the design variables of the natural gas infrastructure, as described in the comprehensive design framework, will assist in the identification of possible convenient design variables that can be altered to mitigate the effect of an implication. The alteration of different variables or a set of variables can lead to the mitigation of an implication. These variables can be technical or market design variables or a combination of them. An analysis will be conducted to identify convenient alterations of variables in the design of the natural gas infrastructure that allow for the successful integration of the specific hydrogen infrastructure configuration.

To get insights in how the natural gas infrastructure can successfully integrate hydrogen, a comparison is made between the results of the two hydrogen infrastructure configurations. The implications of the hydrogen configurations combined with the possible alternations to mitigate the effects of the implications will give insights in the convenience of a potential hydrogen infrastructure configuration. The hydrogen infrastructure configuration will therewith be analyzed in terms of the challenges that it causes for the functioning of the natural gas infrastructure and the convenience to implement the hydrogen configuration.

### **1.3.2 Methods per sub research question**

The first sub research question focusses on the formulation of a theoretical framework to conceptualize both the technical and the market design of the Dutch natural gas infrastructure within the concept of socio-technical systems. The concept of socio-technical systems in this thesis refers to the notion that an energy infrastructure consists of both a physical network and a social network. Moreover, “The behaviour of the infrastructure as a whole cannot be understood by merely studying the structure and behaviour of either.” (Herder et al., 2008, p. 19) The comprehensive design framework forms the basis of this theoretical framework. The theoretical framework is obtained by a literature study in the academic literature on socio-technical systems design and energy infrastructures.

The second sub research question focusses on a description of the natural gas infrastructure within the boundaries of the comprehensive design framework. Variables that are included in the description of the technical design consider the design perspectives, the design principles, and the control mechanisms applicable to the reliable flow of natural gas through the infrastructure (Scholten & Künneke, 2016). Variables that are included in the description of the market design include the formal institutions, the governance, and the organization of the actors applicable to the economically and socially preferred provision of natural gas (Scholten & Künneke, 2016). The description of the Dutch natural gas infrastructure is hence limited to the use of the variables as defined by Scholten & Künneke (2016) in the comprehensive design framework. The description follows the view of energy infrastructures of Scholten & Künneke (2016) and includes the sources, technologies, actors, and institutions involved in the production, transportation, consumption and management of natural gas. The specific technologies for the exploration and extraction of natural gas are excluded from the description. From the description of the natural gas infrastructure, an assessment will be made on the degree of alignment between the technical and market designs. The latter results can contribute to the understanding about the relationship between the degree of alignment and the functioning of the infrastructure. The description of the natural

gas infrastructure follows from the application of the comprehensive design framework. Literature study is used as a supportive method.

The focus of the third sub research question is on identifying potential options to replace (parts of) the natural gas infrastructure with hydrogen infrastructure. The options focus on the replacement of the heat demand in the residential and service sector because of a phase out of natural gas. A feasible hydrogen infrastructure configuration refers to a system based on the use of hydrogen as an energy carrier that can potentially be integrated in the existing gas infrastructure. Feasible refers to the ability of the hydrogen configurations to substitute natural gas in the satisfaction of the heat demand of a specific area in the Netherlands. The hydrogen infrastructure configurations will be selected based on the available and existing use- and test-cases to integrate hydrogen for the reliable, acceptable and affordable provision of heat in the residential and service sector. Transitional issues as trained personal, and political and social support are excluded. The hydrogen configurations selected vary in the hydrogen production technologies that they are based on. Because of the time restrictions of the thesis project, further elaborations or alternatives to these two options will be excluded from the scope of the research. The hydrogen infrastructure configurations are obtained through a literature study and function as the input for the application of the comprehensive design framework.

The fourth sub research question focusses on the identification of the implications of the two hydrogen infrastructure configurations on the functioning of the natural gas infrastructure. Implications refer to the potential problems for the functioning of the Dutch gas infrastructure. The functioning of the infrastructure refers to the desired functioning of the overall heat supply system. That is the available, affordable, and acceptable provision of heat to the Dutch residential and service sector. The focus is therewith on situations where the design of the natural gas infrastructure is currently insufficient to successfully integrate hydrogen. A successful integration of hydrogen refers to an integration of hydrogen that results in an available, affordable, and acceptable heat provision of the substituted demand. The implications are identified by the application of the comprehensive design framework and iterated and validated using semi-structured interviewing.

The focus of the fifth sub research question is on identifying convenient alterations in the design variables of the natural gas infrastructure. Convenient alterations refer to useful and doable technical and institutional alternations in the design of the natural gas infrastructure that have the potential to deal with the identified problems of the hydrogen options. Doable refers here to the possibility of changing a design variable in terms of costs, technology, and legality. Useful refers to the desired effect of the integration in terms solving its implications. The possible alterations in design variables that are researched are limited to the set of variables from the comprehensive design framework. The alterations are identified by the application of the comprehensive design framework. Semi-structured interviewing will be used to iterate and validate the results. The convenient alterations should lead to insight in a hydrogen infrastructure design that can contribute to the Dutch goals on the replacement of natural gas in 2030. The results will be limited to the two researched hydrogen options and to the included design variables. The social and political issues of a transition towards hydrogen are excluded. The representations of the natural gas infrastructure design and the hydrogen are a static description of the variables and their interrelations. Hence, the non-linear behavior of the overall system (the total infrastructure) is not part of the analysis.

### **1.3.3 Elaborating on the research methods**

This section elaborates on the application, limitations, and drawbacks of the research methods as referred to in the previous section. The research methods: applying the comprehensive design framework, literature study, and semi-structured interviewing will be discussed respectively.

#### **1.3.3.1 Application of the comprehensive design framework**

The application of the comprehensive design framework in the thesis project relies on five different steps. These steps are based on the steps defined by Scholten & Künneke (2016, p. 17) and form the core of the research method and are defined as follows:

1. The application of the framework starts with a description of the Dutch natural gas infrastructure. This implies a detailed description of the systemic and institutional environment, the relevant performance criteria of the system, the current technologies and operational practices (i.e. design principles and control mechanisms), and the natural gas-specific governance and modes of organization. The outcome of this step is a clear description of the comprehensive design of the natural gas infrastructure within the concepts of the framework. Based on the comprehensive description, an assessment will be made of the degree of alignment in the current natural gas infrastructure design.
2. The second step of the application is to identify hydrogen infrastructure options that are feasible to be integrated in the Dutch natural gas infrastructure. Once identified, these options will be described in terms of the technologies and operational characteristics that they imply. The outcome are 2 technical hydrogen infrastructure configurations that will be investigated.
3. The third step of the application is to investigate what changes in the natural gas infrastructure design because of the integration of hydrogen. The changes that a hydrogen integration causes will be investigated per hydrogen infrastructure option. This step will be conducted by identifying the elements in the natural gas infrastructure design that need to be added, replaced or adjusted. The outcome of this step is an overview of the change per hydrogen option. Each overview of the hydrogen options represents the implications of its integration for the functioning of the gas infrastructure.
4. The fourth step of the application focusses on the identification and interpretation of these implications. This step considers the problems that occur because of the changes. The focus is on how the other layers of the framework are affected by the changes. The market and operational implications will be identified by analyzing the changes and their consequences. The outcome of this step is a comprehensive overview of the implications per hydrogen option, positioned in the various layers of the framework's dimensions.
5. The last step of the application focusses on the design options to address the implications identified in the previous step. The design options and their trade-offs will be identified. In this step it will be investigated what choices are convenient in the alteration of the current infrastructure design. The outcome is a hydrogen infrastructure configuration that will be discussed along the changes that are needed in the current natural gas infrastructure design.

The application of the framework as described above has some drawbacks. The focus of the application is on finding problems in the functioning of the natural gas infrastructure for the provision of heat to the residential and service sector. The application of the framework hence not focusses on the application of hydrogen in the industry and power generation industry. In principle, if more configurations were included, the research would have given stronger results. The latter is not possible due to the time restrictions of the thesis project. Moreover, the focus of the application of the framework lies on the functioning of the infrastructure and hence on its market and operational implications. Implications in

the installation of the hydrogen technologies, their user interface, and their acceptance are excluded from the framework. The application of the framework is limited to the design variables as stated in the framework. On the one hand, this provides an adequate tool to clearly map the changes and implications in a structured manner. On the other hand, a drawback is that the focus of the analysis is merely on the market and system design concepts (i.e. the economic and technical concepts). The social concepts of the infrastructure are hence insufficiently addressed. Another drawback is that the framework is almost not applied yet, and therewith untested and inadequately operationalized and scrutinized (Scholten & Künneke, 2016). Scholten & Künneke (2016) also state that the framework is not yet able to fully derive design criteria for the institutional arrangements of the infrastructure solely on the technical characteristics of the infrastructure and vice versa. This can be problematic for the fifth step of the application. Another drawback is that the framework focusses on a static representation of the natural gas infrastructure and the hydrogen technologies. The framework therewith only includes the linear behavior of the overall system. Socio-technical systems exhibit a large degree of social, economic and technical complexity that is the result of the non-linear behavior of its elements (Bauer & Herder, 2009). Only considering the linear behavior could introduce problems in the uncertainty of the results of the thesis (Walker, Stanton, Salmon, & Jenkins, 2008). From this uncertainty, it is possible that some changes or implications of the integration of hydrogen are overlooked or interpreted differently.

#### **1.3.3.2 Literature study**

Literature study as a method refers to process of obtaining knowledge from a selection of collected literature. In the thesis project knowledge is needed about the Dutch natural gas infrastructure and the variety of hydrogen options. Moreover, scientific knowledge is needed to form the theoretical framework of the thesis. Literature study is a generic term for studying the available literature. The literature can exist of both non-academic and academic literature available in journals, books, online sources, et cetera.

Literature study is applied as a method to formulate the theoretical framework and therewith answer the first sub research question. For this purpose, academic literature in the fields of socio-technical systems design, energy infrastructures, institutional and system design are consulted to define and conceptualize the main concepts in the thesis. To clearly capture the characteristics of the natural gas infrastructure and answer the second sub research question, literature study is used to obtain the knowledge from a variety of non-academic and academic sources. The same applies to the formulation and definition of the various hydrogen infrastructure configurations (i.e. answering sub research question 3).

#### **1.3.3.3 Semi-structured interviewing**

Interviewing, as a research method, refers to the collection of knowledge by asking an interviewee various question. These questions are usually asked to several interviewees for the purpose of collecting the empirical data that is needed. The questions can be asked in a standardized or non-standardized sequence and can have a varying or fixed content regarding the various interviews that are conducted. The thesis project will apply interviewing as a method to obtain knowledge about the implications of integrating hydrogen. Moreover, interviewing will be used to validate the results obtained from the application of the comprehensive design framework. The interviewing method conducted in the thesis project is referred to as semi-structured interviewing. Semi-structured interviews contain both open and closed questions with a non-standardized sequence but with a consistent content over the several interviews (Gudkova, 2018). The latter is important to gain adequate and valid knowledge about the content of the interviews (Gudkova, 2018). The interviews will be conducted with experts in the field of hydrogen for the purpose of heating the residential and service sector. To prevent bias in the results,

the interviews will be conducted with both academics as non-academics. Seven interviews will be conducted to cover the possibility of subjectivity.

Since the application of the framework is rather untested and open to errors of the specific interpretation of the researcher, the thesis project uses semi-structured interviewing as a method to iterate and validate the application of the comprehensive design framework. Interviews hence consists of questions that are aimed to test the results obtained by the application of the framework and to add useful overlooked insights to these results. Semi-structured interviewing is therewith used as a supportive research method to answer sub research question 4, sub research question 5, and sub research question 6.

### 1.4 Thesis outline and research structure

Figure 2 shows the basic structure of the research conducted in this thesis project.

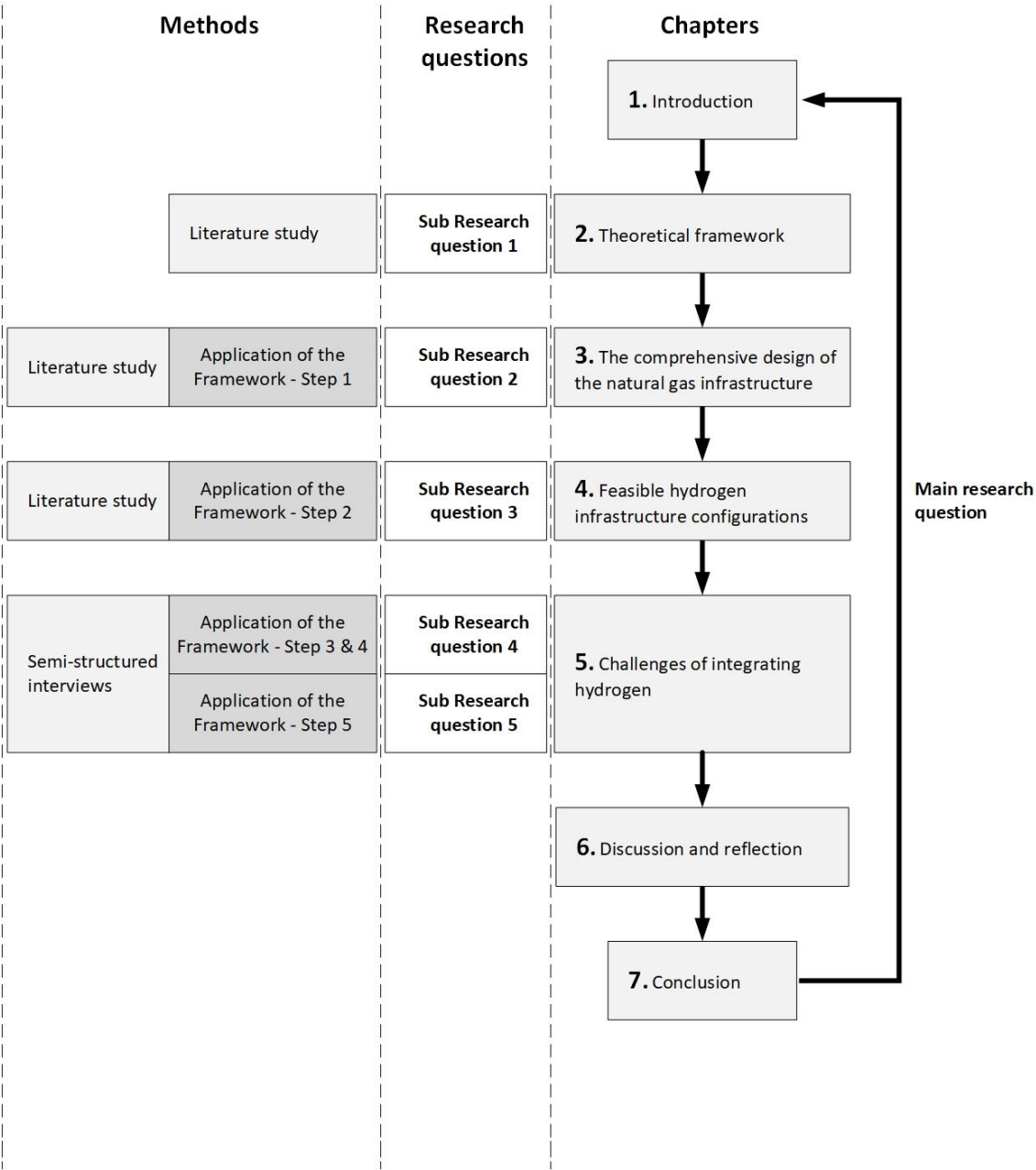


Figure 2: Research flow diagram



## 2. Theoretical framework

This chapter aims to answer the first sub research question, *how can the Dutch natural gas infrastructure be conceptualized in terms of the concepts of socio-technical systems?*

To answer this question a theoretical framework needs to be obtained. The literature about socio-technical systems will provide this framework. Energy infrastructures will be placed in the perspective of socio-technical systems. The performance of energy infrastructures will be discussed and linked to the complementarity in the design of energy infrastructures. The concept of energy system integration will be defined. Next to the theoretical framework, a method needs to be obtained to adequately conceptualize the Dutch natural gas infrastructure in the concepts of socio-technical systems. The comprehensive design framework provides this method.

This chapter will elaborate on the comprehensive design framework and its application. Paragraph 2.1 discusses the theoretical framework. Paragraph 2.2 elaborates on the comprehensive design framework. Paragraph 2.3 discusses the operationalization of the comprehensive design issue and the application of the framework.

### 2.1 Socio-technical systems

The early work on socio-technical systems is mainly based on the research in the field of large technical systems (LTS). This body of knowledge is considerably initiated by Hughes' (1983) work on the development of large technical systems in the power sector. Other than most research back then, Hughes included not only the technical but also the societal and cultural contexts of systems. Hughes (1983, p.481) identified that power systems encompass both “a technical core of components as well as institutional components” and that “Such encompassing systems should be labeled as socio-technical systems rather than technological systems”. The relevance of both the technical and institutional dimensions of energy systems is therewith recognized early on by Hughes. Large technical systems were studied by many scholars from different disciplines with different technical systems as the object of study (Ewertsson & Ingelstam, 2005). In these studies, consensus existed about the importance of both the social and technical dimension of the overall system (Ewertsson & Ingelstam, 2005). It is conceived that Large technical systems are structured around a technical core of physical artifacts that are embedded in, sustained by, and interact with comprehensive socio-historical contexts (Ewertsson & Ingelstam, 2005; Hughes, 1983). The latter is fundamental and suggest that the technological dimension of socio-technical systems is shaped by its interaction with the society where it is created, adapted and developed (Ewertsson & Ingelstam, 2005).

More recent literature on socio-technical theory is focused on the interaction between the social and technical dimension of systems and the understanding of how they should be designed to function well together. Socio-technical theory is basically founded in two main principles. First, the interaction between the social and technical elements of a system determines the successful performance of a system (Walker et al., 2008). Second, the single optimization of either the social elements or the technical elements tend to increase the unpredictable, non-linear outcome of the system (Walker et al., 2008). The complex non-linear behavior of an energy system, as a result of the interaction of its social and technological elements, is hard to capture (Walker et al., 2008). Socio-technical theory is about the understanding and conceptualization of this complexity. The joint optimization of the social and technical elements of a system is hence an important part in socio-technical research. Complex socio-technical systems are defined as “ensembles of technical artifacts embedded in society, connected with

natural ecosystems, functioning within regulatory frameworks and markets, and exhibiting a high degree of complexity and dynamics that are not fully understood” (Siddiqi & Collins, 2017, p.7).

### **2.1.1 Socio-technical perspective on energy infrastructures**

Energy infrastructures are conceived to be adaptive complex socio-technical systems with strongly interwoven technical and institutional elements that need a comprehensive approach in analysis and design (Bruijn & Herder, 2009; Chappin & van der Lei, 2014; Crettenand & Finger, 2013; Houwing, Heijnen, & Bouwmans, 2006; Künneke, Groenewegen, & Ménard, 2010; Van der Lei et al., 2010). The energy infrastructures comprise out of a variety of interlinked social and technical components that need to be attuned in order to function in a harmonious way that result in a desired system performance. Finger, Groenewegen, & Künneke (2005, p. 229) highlight three key features of infrastructures:

*“Firstly infrastructures are based on physical networks. The allocation of goods and services is provided through these networks and they therefore constitute an important technical and economic backbone for the functioning of the related industries. Secondly, infrastructures pose challenges to institutional governance. Traditional market oriented solutions are often not possible since severe forms of market failures are involved. This includes the occurrence of positive or negative external effects, collective goods, increasing returns and network effects. Therefore some supporting regulation is warranted to ensure the proper functioning of these sectors. Thirdly infrastructures serve major social objectives or needs that are of significant economic and political importance. Infrastructures are seen as an important foundation for the functioning of modern political and economic systems. Accordingly, politics is directly or indirectly involved in monitoring or even controlling the performance of these sectors.”*

These three features stress the importance of a comprehensive view on infrastructures and highlight the interrelatedness of the social, economic and technical elements of an infrastructure. Hence, the interrelatedness emphasizes the importance of simultaneously considering the technical, economic and social perspectives in the analysis of an infrastructure. This refers to the idea that if one dimension of an infrastructure is optimized in isolation, the dynamics of a socio-technical system cannot be adequately addressed, and uncertainties can occur in the outcome of the system.

An energy infrastructure, as defined by Houwing et al. (2006, p.907), is “the total system of generation, transport, distribution, trade, supply and consumption of energy. This means not only the physical network (e.g. power plants, gas pipes, heat delivery stations), but also the social (economic and institutional) network that manages and controls the physical system.” This definition of energy infrastructures also recognizes the importance of the interrelatedness of the social-economic and technical dimension in the management and control of energy infrastructures. The interaction between the techno-operational characteristics, energy market dynamics, and institutional arrangements is hence a crucial determinant for the system performance (Scholten & Künneke, 2016).

The physical network of an energy infrastructure (i.e. the technical dimension), comprises of the tangible technological components that guide the flow of energy. The social-economic dimension consists of the institutions, i.e. non-tangible components, that guide the social-economic activities that occur within energy infrastructures. The configuration of both dimensions and their interactions need to result in a reliable, affordable and acceptable provision of energy. Technically, energy infrastructures are conceived to be adaptive systems (Finger et al., 2005; Scholten & Künneke, 2016). Adaptive refers to the capacity of a infrastructures to resist or to adapt to a particular situation of distress in order to maintain an acceptable level of performance (Finger et al., 2005). The latter stresses an important

function of energy infrastructures, which is providing a reliable flow of energy. Socially, infrastructures are conceived to be of major importance in fulfilling societal needs. This stresses other essential functions of energy infrastructures, hence the affordable and acceptable provision of energy. The configuration of the different technical options determine how the flow of energy is controlled and managed through the supply chain in order to be reliable and robust (Scholten & Künneke, 2016). The configuration of the institutions determine how the economic efficient and effective allocation of energy can be achieved in a way that meets the needs of the public (Scholten & Künneke, 2016). Both the technical dimension as the social dimension, and their interrelation determine the outcome of the energy infrastructure.

In energy infrastructures, “performance is about how institutions and technical options incentivize actors and shape activities in the commodity and monetary flows” (Scholten & Künneke, 2016, p. 3). The commodity flow refers to the physical assets and artifacts that function together as a supply chain, as well as their accompanying operational activities in order to coordinate and control the physical flow of energy (Scholten & Künneke, 2016). The existing technology sets the boundaries for what is technically and operationally feasible (Scholten & Künneke, 2016). The monetary flow relates to the transactions that occur in the energy markets (Scholten & Künneke, 2016). The formal and informal institutions structure the transactions within the market. The institutional design and the technological design determine how actors engage in transactions and technical operational activities and therewith how actors behave within the monetary and commodity flow of an energy infrastructure (Scholten & Künneke, 2016).

In analyzing energy infrastructures, it is thus important to notion that the social network and the physical network are interconnected and that they influence each other’s development (Herder et al., 2008). The behavior of an energy infrastructure from a system perspective, is only poorly understood by analyzing the structure and the behavior of the social or technical network in isolation (Herder et al., 2008). Engineers are merely focused on the technical-operational subsystems of an energy infrastructure, where economists, legal experts and policy makers are focused on the economic-institutional subsystems. These various perspectives are all necessary to understand the dimension specific-complexity within an energy infrastructure (Herder et al., 2008). Besides the dimension specific complexity, the interrelation between the social and technical elements of an energy infrastructure adds another domain of complexity to the analysis of energy infrastructures (Herder et al., 2008). This domain of complexity raises the need for a conceptualization of energy infrastructures that considers all the social, technical and economic elements of the system together. Such a comprehensive conceptualization is needed to capture the complexity of the interactions between the social, economic and technical networks of the infrastructure.

### **2.1.2 Performance of energy infrastructures**

The performance of energy infrastructures is generally defined by the energy trilemma. The energy trilemma refers to the three performance dimensions of availability, adorability, and acceptability of the energy provision. According to the World Energy Council (2017, p. 9), the sustainability of the energy system is also based on these three dimensions, formulated as - energy security, energy equity, and environmental sustainability. These three dimensions include different performance criteria. The performance criteria of the energy trilemma are defined by the World Energy Council (2017, p. 9) in the following way:

- energy security: “Effective management of primary energy supply from domestic and external sources, reliability of energy infrastructure, and ability of energy providers to meet current and future demand.”
- energy equity: “Accessibility and affordability of energy supply across the population.”

- environmental sustainability: “Encompasses achievement of supply- and demand-side energy efficiencies and development of energy supply from renewable and other low-carbon sources.”

Achieving a high performance on all three dimensions would generally mean that the system performs well economically, social-politically, and technically (Finger et al., 2005).

### **2.1.3 Complementarity in energy infrastructures**

The performance of energy infrastructures is an extensive concept that refers to the several social, political, and economic functions of the infrastructure (Finger et al., 2005). Complementarity is defined by the Cambridge English Dictionary (2018) as “the state of working usefully together.” The concept of complementarity in the thesis refers to the notion that the design of a specific element of the infrastructure cannot obstruct the functioning of another element and therewith the performance of the overall system. The performance of an energy infrastructure is conceived to be largely dependent on the complementarity of its techno-operational and economic-institutional components (Finger, Crettenand, & Lemstra, 2015; Finger et al., 2005; Künneke et al., 2010; Scholten & Künneke, 2016).

Energy infrastructures are complex technical systems with a strong degree of technical complementarity (Künneke, 2013). This refers to the notion that all major elements technically interact with each other in a specific manner to provide a reliable and robust energy provision (Künneke, 2013). Finger et al. (2005) identify four system relevant functions that need to be assured to allow for complementarity in the system. These functions are interconnection, interoperability, capacity management, and system management (Finger et al., 2005). “Interconnection deals with the physical linkages of different networks that perform similar or complementary tasks.” (Finger et al., 2005, p. 240) “Interoperability is realized if mutual interactions between network elements are enabled in order to facilitate systems’ complementarity.” (Finger et al., 2005, p. 240) “Capacity management deals with the allocation of scarce network capacity to certain users or appliances.” (Finger et al., 2005, p. 241) And, “system management pertains to the question of how the overall system (e.g., the flow between the various nodes and links) is being managed and how the quality of service is safeguarded.” (Finger et al., 2005, p. 241) Complementarity in the system can thus be achieved if the system relevant functions are assured by proper technological and institutional designs. Building upon the literature on alignment of institutions and technology<sup>1</sup>, complementarity in energy infrastructures can be defined as: the state of an energy infrastructure in which the system relevant functions are assured and all the techno-operational and economic-institutional elements of the system function acceptably together. A certain degree of alignment between institutions and technology is hence necessary for the system to function. The degree to which the institutions and technologies should be aligned is rather unclear (Crettenand & Finger, 2013)

### **2.1.4 Energy system integration**

The integration of hydrogen in this thesis project refers to the act of integrating hydrogen in the natural gas infrastructure, and to the process of adapting the existing technical and institutional sub-systems for that purpose. System integration thus both involves the actual integration of a new system element and the blending and coordination of the different elements and structures of a system to function well together after the integration (Sage & Lynch, 1999). The blending and coordination of the different elements refers here to the process of reaching a certain degree of complementarity between the various system components. The technical sub-systems of an energy infrastructure need to be designed to function well together and the same applies to the institutional sub-systems of an energy infrastructure.

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<sup>1</sup> See for instance, Crettenand & Finger (2013); Finger et al. (2015, 2005); Künneke (2013); Künneke & Finger (2007); Künneke et al. (2010)

As stressed by Scholten & Künneke (2016), the technical and institutional design practices are often conducted without considering the effects of one design dimension on the functioning of the other. This can be troublesome for the integration of hydrogen since the interrelation between the technical and institutional dimension of energy infrastructure design can be overlooked (Scholten & Künneke, 2016).

The thesis follows the definition of energy system integration as defined by Verzijlbergh, De Vries, Dijkema, & Herder (2014, p. 2): “The process of jointly shaping the technical and institutional sub-systems in a way that supports the transition to a renewable, affordable, and reliable energy system.” This definition stresses the importance of jointly considering the technical and institutional designs of the natural gas infrastructure to investigate the requirements and implications of an integration of hydrogen. In the thesis, it will be investigated how the system integration of hydrogen affects the overall system complementarity and therewith the system performance of the natural gas infrastructure.

### 2.2 The comprehensive design framework

The comprehensive design framework considers the economic and technical dimension of energy infrastructure design that can be aligned along three different layers of abstraction. The economic dimension, refers to the monetary flow within energy infrastructures and the technical dimension refers to the commodity flow of energy infrastructures (Scholten & Künneke, 2016). These dimensions can be aligned in terms of the principles defined by Scholten & Künneke (2016) on access, responsibilities and coordination within energy infrastructures. Figure 3 illustrates the visualization of the comprehensive design framework.

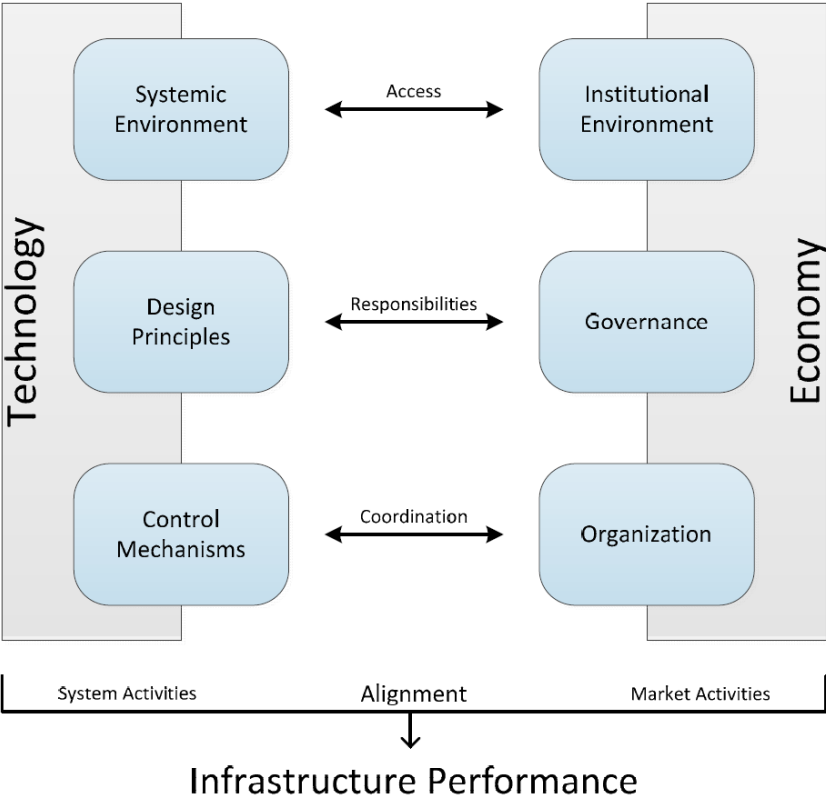


Figure 3: Comprehensive design Framework, adopted from Scholten & Künneke (2016, p. 14)

The complementarity of an energy system is thus approached at three different levels abstraction (Scholten & Künneke, 2016). That is, between the systemic environment and the institutional environment, between the design principles and the governance arrangements, and between the control

mechanisms and modes of organization (Scholten & Künneke, 2016). Every dimension is subject to specific design variables that are assigned to each layer of abstraction. The systems activities and market activities are structured by the configuration of the specific design variables of the concerned dimensions, and the interaction between the design dimensions. Eventually the infrastructure performance is determined by the system and market activities (Scholten & Künneke, 2016). The alignment between the dimensions over the several layers of abstraction can have a positive or negative impact on the infrastructure performance.

### 2.2.1 The engineering design variables of energy infrastructures

The design variables and concepts of the engineering perspective and the institutional perspective on energy infrastructure design are structured based on the four levels of social analysis of Williamson (1998, p. 26). In this way, Scholten & Künneke (2016) reconfigure the existing insights on energy infrastructure design and sort the design variables in order to make them comparable between the technical and economic dimensions. Hence, the core idea of a comprehensive design is that the same layers in both dimensions apply to linkable design variables and concepts (Scholten & Künneke, 2016). Figure 4 shows the various layers of design variables and concepts of engineering design. The choices that engineers make are shaped by the existing technical possibilities available and have concrete implications for the decision making process of actors regarding daily operations (Scholten & Künneke, 2016). It is of importance to notion that “the technological environment (layers 1 and 2a) frames the setting for the design principles and control mechanism (layers 2b and 3), which enable and constrain the actor behavior on the fourth layer” (Scholten & Künneke, 2016, p. 10).

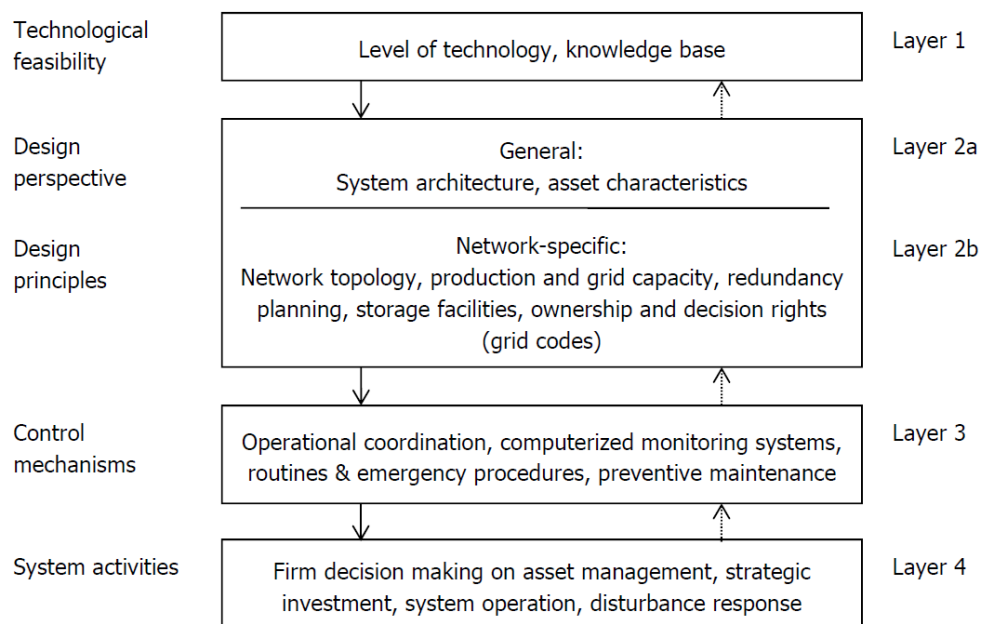


Figure 4: four levels of design variables in the engineering design of energy infrastructures, adopted from Scholten & Künneke (2016, p. 10)

The first layer concerns the existing conceptual and practical knowledge on technology present within society (Scholten & Künneke, 2016). The level of technology and the knowledge on technology are not subject to calculative behavior or purposeful engineering design (Scholten & Künneke, 2016). Instead, they emerge and change slowly and spontaneous out of creative innovation processes within society (Scholten & Künneke, 2016). The technological feasibility is therewith not designable but merely subject to a gradual process of gaining knowledge that can be influenced through policy makers by the stimulation of innovation or for example education (Scholten & Künneke, 2016).

The second layer is separated within two layers, layer 2a and layer 2b. Layer 2a refers to the generic infrastructure design, that is the fundamental organizational choices on the interactions of the different technical components with each other and with their environment. Typical choices on the design perspective are if the system should have an open or a closed system architecture, and if the system should be organized in a decentralized or centralized nature (Scholten & Künneke, 2016). Other design perspective choices include choices on the asset characteristics of the generation, transportation, storage, and application technologies within the infrastructure (Scholten & Künneke, 2016). The latter choices on the design perspective of an energy infrastructure give the context in which the choices on the specific design principles can be made. The choices on the design principles refer to layer 2b. Within this layer the choices are made considering the specific design of energy infrastructures and its operations. Key here, is the knowledge about the technical infrastructure design principles regarding network topology, production, network and storage capacity, redundancy planning, and options for ICT based rerouting (Scholten & Künneke, 2016). Ownership and decision rights need to be defined to govern the essential infrastructure functions of an energy infrastructure. It needs to be clear which actors are responsible for the planning, development, operations, and maintenance of the particular assets (Scholten & Künneke, 2016).

The third layer is concerned with the control mechanisms that need to ensure the reliable operations of the infrastructure (Scholten & Künneke, 2016). This entails the coordination of the reliable flow of energy through the infrastructure, that is the coordination on the operational level. Decisions need to be made on what control mechanisms and technologies are feasible to ensure the reliable operations of the infrastructure. Typical control mechanisms are computerized monitoring systems, routines and emergency procedures and preventive maintenance (Scholten & Künneke, 2016).

The fourth layer concerns the decision making of firms, regarding asset management, strategic investment, the system operation, and the disturbance response (Scholten & Künneke, 2016). The decision-making processes, i.e. the system activities, are structured by the different choices on design variables and design principles. Concerning the robustness and reliability of the energy provision, it is convenient if the firms can adequately make their decisions within the structure of the infrastructure design (i.e. the former layers of design variables in the engineering design). Ensuring the system relevant functions should be adequately addressed. The individual system activities, conducted by different actors, determine the overall system performance of an energy infrastructure. That is, the reliable and robust provision of energy.

### **2.2.2 The economic-institutional design variables of energy infrastructures**

The design variables and concepts of the economic dimension are based on institutional design.

Different economic institutions are distinguished along the different levels of social analysis of Williamson (1998). Figure 5 shows the four layers of economic institutions in the design of energy infrastructures, as conceptualized in the comprehensive design framework. It is important to notion that “the institutional environment (layers 1 and 2a) frames the setting for the governance and organizational arrangements (layers 2b and 3) which in turn incentivize actor behavior on the fourth layer” (Scholten & Künneke, 2016, p. 12).

The first layer relates to the informal institutions that are not subject to calculative behavior or purposeful design (Scholten & Künneke, 2016). The social rules embedded in religion, customs, traditions, and norms and values emerge spontaneously out of the interactions of millions of actors and change slowly over time (Scholten & Künneke, 2016). Hence, these informal institutions are embedded in societies’

cultures and therewith not designable. Informal institutions determine what the design space is of the ‘designable’ formal institutions. Moreover, they also define, to a considerable extent, what a socially preferred outcome is of the energy infrastructures.

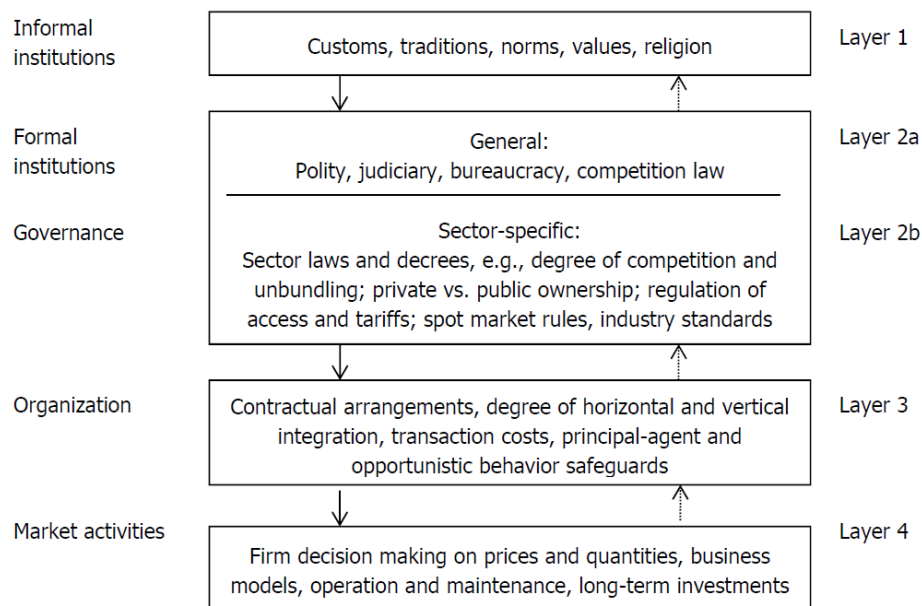


Figure 5: four levels of design variables in the economic-institutional design of energy infrastructures, adopted from Scholten & Künneke (2016, p. 10)

Layer 2a relates to the formal institutions, such as laws and regulations (Scholten & Künneke, 2016). Very generally, the formal institutions relate to how the overall social system should be organized. That are the fundamental choices on the organization of the political-bureaucratic system of a country or union, its state-society relations and its judiciary. These formal institutions should be designed to provide the adequate incentives for actors to interact in such a way that is societally preferred (Scholten & Künneke, 2016). From an economic perspective, a socially preferred outcome would be to maximize the overall welfare, often by monetizing social values. Layer 2b is concerned with the sector specific formal institutions of energy infrastructures, i.e. the governance of energy infrastructures. Core design issues in the governance of energy infrastructures are competition, ownership and regulation (Scholten & Künneke, 2016). Competition refers to the design choice on the right market structure that should provide economic efficiency (Scholten & Künneke, 2016). Important determining factors of choosing the right market structure in energy infrastructures are the possibilities of liberalization, possibilities for substitution, the type of good or service, and the position of the good or service in the life-cycle (Scholten & Künneke, 2016). Ownership refers to the allocation of private and public ownership and decision rights, i.e. private and public property rights (Scholten & Künneke, 2016). Property rights structure the incentives of actors for resource use, they are the set of formal and informal rights to use and transfer resources (Alston & Mueller, 2005). Different sets of property rights incentivize the behavior of actors differently (Scholten & Künneke, 2016). Design choices need to be made regarding to the adequate allocation of property rights to achieve a desired outcome. Sector-specific regulation refers to the institutions that specifically target what is societally preferred within a particular sector (Scholten & Künneke, 2016). Economically, this can be to address market imperfections to achieve economic efficiency. Broader on societal values, sector specific regulation targets values as privacy, universal access, sustainability, safety and health, freedom from bias etc. These sector-specific regulations are institutions of governance that control the goals and activities set out by policies.



The third layer is concerned with the modes of organization that need to ensure an economic efficient and societally preferred outcome of the energy provision. From an economic perspective, attention goes to the modes of organization that structure the market transactions (Scholten & Künneke, 2016). The important design choice is on what modes of organizations should coordinate a transaction. Important considerations are on how to establish the transactions of actors in a manner that results in a desired outcome.

The fourth layer is concerned with the decision making on market activities of firms, structured by the institutional design. Company internal decision making on prices, quantities, investments, business models, optimization of operation and maintenance activities determine the overall outcome of an energy infrastructure (Scholten & Künneke, 2016). That is, the availability, affordability and acceptability of energy.

### **2.2.3 The link between system and market design**

The four layers of design variables in engineering and market design, relate to the generic design of energy infrastructures, the specific design of infrastructures and the interactions between the different actors within the infrastructure (Scholten & Künneke, 2016). The systemic environment (Layer 1 and 2a from the engineering design) and the institutional environment (layer 1 and 2a form the economic-institutional design) relate to the generic design of energy infrastructures. The design principles (layer 2b from the engineering design) and the governance structures (layer 2b from the institutional-economic design) are concerned with the specific design of an energy infrastructure. And the control mechanisms (layer 3 from the engineering design) and the modes of organization (layer 3 from the economic-institutional design) deal with the way different actors interact. These design perspectives can be linked through its access, responsibilities and coordination principles.

The generic design of energy infrastructures is referred to as the “access” layer of energy infrastructure design. Within this layer a rough distinction is made between open and closed access, this distinction determines therewith how an energy infrastructure is designed from a generic design perspective. A closed access perspective on the technical dimension is characterized by “an infrastructure in which only dedicated actors or agencies are allowed to provide a limited number of standardized services.” (Scholten & Künneke, 2016, p. 14) The technical system architecture is characterized by “centralized hubs that monitor critical technical functions, by pre-determined relations between nodes and links, and by a priori planned and directed intervention efforts by appointed entities.” (Scholten & Künneke, 2016, p. 14) Open access, on the other hand, refers to an energy infrastructure that is accessible for all actors that are willing and able to contribute to its service provision (Scholten & Künneke, 2016). The technical system architecture is based on protocols, standards and requirements that actors must oblige if they want to participate in the service provision. Looking at the access principles in the economic-institutional dimension, the institutional environment within an energy infrastructure can rather be oriented at a state or a market perspective (Scholten & Künneke, 2016). Viewing energy transactions from a classic market perspective, a market is competitive and dynamic, and can be entered by new entrants if they comply with the market entry requirements (Scholten & Künneke, 2016). From a state perspective, the transactions are strictly controlled by state regulations in a more static and monopolistic manner.

The specific design perspective of an energy infrastructure relates to the “responsibilities” layer of energy infrastructure design. The responsibilities layer refers to the allocation of the various responsibilities to different actors within the operation of an energy infrastructure. The question here is, in which way the “control and intervention tasks regarding technical operations and ownership and

decision rights concerning market transactions (and public service context) are or should be divided at a specific location and time within the systemic and institutional context” (Scholten & Künneke, 2016, p. 15). Typical technical operational tasks are on the choice and management of assets and control systems (Scholten & Künneke, 2016). Responsibilities can be divided under public and private actors, and deal with the authority to carry out certain operational and intervention tasks, and make investment decisions on certain assets (Scholten & Künneke, 2016). “Economically, specific ownership and decision rights are assigned to companies as part of broader sectoral decisions regarding competition, privatization and regulation.” (Scholten & Künneke, 2016, p. 15) The responsibilities that are allocated via the ownership and decision rights need to result in market transactions that achieve an economic efficient and societally preferred outcome.

The coordination between the interactions of different actors within the energy infrastructure is referred to as the “coordination” layer of energy infrastructure design. This layer is concerned with the coordinational arrangements that need to structure the actor behavior in such a way that the accumulative results in a desired performance of infrastructures. Technically, the coordination “relates to the nature of an interaction among actors involved in an operational activity.” (Scholten & Künneke, 2016, p. 15) Coordination mechanisms variate in perspective from centralized forms of coordination to more autonomously operating units (Scholten & Künneke, 2016). These coordination mechanisms are generally determined by the complexity of the interactions and the technical networks, and the speed in which they need to be coordinated (Scholten & Künneke, 2016). Economically, coordination relates to the nature of the transactions among actors under given property rights, market structure, and regulation (Scholten & Künneke, 2016). Modes of organization regarding the transactions of actors variate mostly from the preference of private contracting to vertical integration. The question is about whether the control mechanisms and modes of organization should be organized in a centralized or decentralized way.

#### **2.2.4 The comprehensive design issues**

The comprehensive design framework allows for the linkage between the various layers of the technical and economic dimension of energy infrastructures (Scholten & Künneke, 2016). “This linkages make it possible to relate design steps in one dimension to those of another” (Scholten & Künneke, 2016, p. 18). This approach moves beyond the single perspective of optimizing either system or market design (Scholten & Künneke, 2016). The comprehensive design issue exists within these linkages. Every linkage implies the question of how the technical and economic dimensions should be aligned on the level of that linkage, i.e. looking at the design steps in that linkage.

##### **2.2.4.1 The issue of alignment in access**

From a generic perspective of infrastructure design (access layer), technology and institutions can be linked in the way they provide the solution space for the energy infrastructures to function in. Technically, this solution space is defined by the technical feasibility of a region or country at a certain time. Structured by this technological feasibility, and influenced by the institutional environment, different fundamental choices are made on the design perspective of an energy infrastructure. Economically, the solution space is defined by the informal institutions that are institutions of culture in a specific region or country. The formal institutions are strongly influenced by the informal institutions and need to support the technical system architecture of an energy infrastructure. Moreover, the formal institutions are there to structure the actor behavior in an energy infrastructure in such a way that it generates societally preferred and economic efficient outcomes. The way access is provided to the energy market and the operational activities of the energy provision, determines to a large extent what

the general infrastructure design set up is. The question of alignment in the generic perspective on energy infrastructure design is:

*Do the system architecture and the characteristics of the assets imply the same principles of open and closed access as the formal state institutions?*

Important here is to separate this question in three parts: the organization of access in the technical dimension, the organization of access in the economic dimension, and the question whether the principles of open and closed access are contradicting in both dimensions. First, it needs to be determined which actors are allowed through which mechanisms to participate in the service provision of an energy infrastructure on a specific location and time. Important here is the way in which access is provided to the technical operational activities of an energy infrastructure. By analyzing the access principles applied to the technical dimension of the infrastructure, the access principle and its consequences can be identified. Second, it is important to consider the access principles within the economic dimension of the energy infrastructure. It needs to be determined which actors can enter the market under what conditions. The emphasis is on the conditions for entering the energy market. Third, the access principles of both dimensions can contradict. If the economic and technical dimension exhibit significantly different access principles, it can result in perverse effects on the provision of energy.

#### **2.2.4.2 The issue of alignment is responsibilities**

From a more specific design perspective on energy infrastructures (i.e. the responsibilities layer), the question of alignment looks at the allocation of responsibilities regarding the different market and operational activities. The technical design dimension focusses on how to structure the technical operational activities and the economic design dimension focusses on how to structure the market activities. The question of alignment within this layer is:

*How should the control and intervention tasks be allocated in a way that they do not obstruct with the allocation of ownership and decision rights and therewith do not hamper the functioning of the other dimension (and vice versa)?*

This question can, in analogy with the access layer, be separated in three parts. Looking at the allocation of responsibilities regarding the control and intervention tasks (i.e. the technical dimension), looking at the allocation of responsibilities regarding the market activities (i.e. the economic dimension), and to look at how the allocation of the responsibilities in both dimensions should be attuned. First, it needs to be determined which actors have the authority to perform certain technical operational and intervention tasks and may decide on investments. An important question is which actors are responsible for what system activities at a specific location or in a specific subsystem at a specific time. Actors can share the responsibility or be responsible for several different components of the technical infrastructure. Second, it is important to look at the ownership and decision rights concerning the market transactions and public service obligations in the energy infrastructure. Which actors, public or private, have certain ownership and decision rights within the broader context of competition, privatization and regulation? Third, in the design process of an energy infrastructure one should consider that the allocation of responsibilities in one dimension does not obstruct the proper functioning of the other (and vice versa). For example, is the scope of control to handle technical operational activities coherent with the role of the same specific company in the energy market? The allocation of responsibilities in both dimensions need to be attuned to some extent and fit into the systemic and institutional context of the energy infrastructure design.

### **2.2.4.3 The issue of alignment in coordination**

Looking at the coordination of the control and intervention tasks (i.e. coordination of a reliable flow of energy), and the different modes of organization (organization of economic efficient and societally preferred service provision), it is important to look alignment from the way in which the essential functions of an energy infrastructure are guaranteed. The technical dimension of design focusses on how to adequately coordinate the technical critical functions of an infrastructure. The economic dimension of design is focused on guaranteeing an economic efficient and socially preferred outcome of the variety of market activities. The question of alignment within the coordination layer is:

*Does the way the technical operational tasks are coordinated lead to perverse effects of the organization of the market activities (and vice versa)?*

This question, in analogy with the issue of alignment in the access and responsibilities layer, focuses on the technical dimension, the economic dimension and the alignment issue between both. First, in the technical dimension, it is important to identify which technical operational activities are there. Important questions are whether these activities are related to the critical technical functions of an infrastructure and how they should be controlled. Hence, the actors need to be identified that are involved within the variety of the technical operational activities and their coordination. Per specific technical operation activity, it can be identified if the activity is controlled either in a centralized or decentralized fashion. Economically, it is important to look at the different transactions that occur within the energy infrastructure and if they are there to support the critical technical functions of the infrastructure. The actors that are involved in the several transactions need to be identified, and the way in which they are coordinated by for example private contracting or vertical integration needs to be considered. The question of alignment aims at linking the coordination mechanisms of both dimensions to be better attuned. Both the coordination of the technical operation activities and the market transactions need to fit in the design principles and governance arrangements active within the energy infrastructure.

### **2.2.5 Concluding remarks using of the comprehensive design framework**

The comprehensive design framework is a proper theoretical framework for the structured mapping of the technical and economic dimensions of the natural gas infrastructure design. Moreover, it allows to explore the changes of an integration of hydrogen in the natural gas infrastructure in a structured manner (Scholten & Künneke, 2016). The framework also provides an adequate method to link both design dimensions over the various layers of abstraction defined in the framework. The latter function makes the framework suitable for the analysis towards the potential implications and requirements that an integration of hydrogen has for the functioning of the natural gas infrastructure. In analyzing the alignment between the technical and institutional elements of the natural gas infrastructure design, alignment remains a rather fuzzy concept. The comprehensive design framework operationalizes alignment in a dichotomous way. One dimension either obstructs the functioning of the other or not. To broaden the understanding of the degree of alignment between the institutional and technological elements of the energy infrastructure, an attempt is made to further operationalize alignment. Paragraph 2.3 elaborates on this operationalization

## **2.3 Operationalization of the comprehensive design issue**

Looking at the issues of alignment described earlier, alignment is operationalized in a dichotomous way. In the access layer, technology and institutions either follow principles of closed access or open access. In the responsibilities layer, a similar feature is visible. The allocation of responsibilities to actors in one layer can obstruct the allocation in the other layer in its functioning. Hence, the allocation of

responsibilities either shows complementarity or not. In the coordination layer coordination mechanism and modes of organization vary among centralized and decentralized forms. The notion is that technology and institutions should exhibit the same form of coordination and organization.

To further understand the relationship between technology and institutions, it is proposed to further operationalize alignment. As an addition to the comprehensive design framework, it is proposed to add more categories of how to typify the access, responsibilities and coordination layers within both dimensions of the comprehensive design framework. That is, to define four categories for every issue of alignment for both dimensions to be better equipped to analyze the way in which alignment effects the functioning of the infrastructure. Table 1 shows an overview of the categories per dimension, per layer. The categories are inspired by the ideas on the alignment of the technical critical functions and the modes of organization of Künneke et al. (2010) and the ideas of Scholten (2013) on the coordination of multiple actors for a reliable operation of energy infrastructures.

<b>Techno-operational dimension</b>				
<b>Layer</b>	Most stringent regulated $\longrightarrow$			Least stringent regulated
Access	Closed access	Access through Property rights infringement	Conditional access	Open access
Responsibilities	Public responsibility	Delegated responsibility	Arbitral Responsibility	Decentralized responsibility
Coordination	Public coordination	Decision rights infringement	Conditional coordination	Incidental coordination
<b>Economic-institutional dimension</b>				
<b>Layer</b>	Regulated by the state $\longrightarrow$			Facilitated by the market
Access	Closed access	Delegated access	Conditional access	Open access
Responsibilities	Public responsibility	Public-private responsibility	Monitored responsibility	Decentralized responsibility
Coordination	Public coordination	Public-private coordination	Conditional coordination	Decentralized coordination

Table 1: Overview categorization different layers of the comprehensive design of energy infrastructures

These categories refer to different modes of regulating access, allocating responsibilities, and organizing coordination in both dimensions of energy infrastructure design. Inspired by Künneke et al. (2010), the way in which the layers can be operationalized is strongly related to the requirement of directive intervention and the requirement of authoritative supervision. With lower binding needs for these requirements, regulations can become less stringent. The operationalization of the layers of abstraction in the technical and economic dimension will be defined in this section.

### 2.3.1 Categorization of the technical dimension of Access

Within the access layer, a distinction is made between closed access, access through property rights infringement, conditional access, and open access. The requirement for authoritative supervision and the requirement for directive intervention is most stringent with the closed access principles and the least

stringent with the open access principles. The authority to make decisions on operational activities and asset management of the energy infrastructure is defined as the allowance to participate in the service provision of an energy infrastructure.

Closed access refers to access regulation in a way that *only dedicated actors can participate in a limited number of standardized services under the authority of a regulator*. The technical architecture of the energy infrastructure is “characterized by centralized hubs that monitor and control critical technical functions, by pre-determined relations between the nodes and links, and a priori planned and directed intervention efforts by appointed entities.” (Scholten & Künneke, 2016, p. 14) An example of a closed access principle exists in the management of the natural gas transmission grid. A system operator, under supervision of a regulator, has the full authority to change the operation and management of the infrastructure and control the way in which the transmission system is operated and designed.

The access through property rights infringement principal rests on the notion that an operational failure does not have system wide consequences, but the effects of a failure can be severe. This is for example the case when considering the extraction of natural gas. Congestion in one of the production systems does not immediately lead to system wide consequences. Failures can result in serious safety and environmental hazards. The way in which the total system is designed and operated remains under control of one single public entity to safeguard the complementarity of the different systems. Property rights infringement access is defined as *access through the approval of the public infringement of an entities' property rights*.

Conditional access is defined *access through a license or permit obtained from a public supervisory body*. The way the system is designed and operated does need to comply with clear safety, environmental and economic norms and standards. Supervision and a degree of control on the design and operation of the assets still need to exist. The latter form of access can be linked to the management of the underground gas storage facilities.

Open access refers to a situation where *all actors that are willing to and able to contribute to its services are allowed to provide services within the active regulatory framework*. These infrastructures rely on “protocols, standards or procedures that firms or agencies have to adhere to if they want to participate.” (Scholten & Künneke, 2016, p. 15). Open access “allows for the spontaneous and unanticipated development of infrastructure components and provides a potentially broad range of services directed towards different users” (Scholten & Künneke, 2016, p. 15). The latter form of access is hardly applicable to the highly regulated nature of the technical energy infrastructure.

### **2.3.2 Categorization of the technical dimension of responsibilities**

The allocation of responsibilities needs to be complementary with the principles on the regulation of access. Actors can have different responsibilities in technical operational activities and asset management of specific components, subsystems and systems. Public responsibility refers to a situation where the requirement on directive intervention and the requirement on authoritative supervision is the most stringent. Decentralized responsibility refers to the situation where the requirements are the least stringent.

Public responsibility is defined as an allocation of responsibilities where *one public entity is responsible for both the control and intervention decisions regarding the technical operations and asset management*. An example is the transmission system operator that is responsible for all the decisions on

the technical operation and asset management of the transmission system. Entities can interact within the strict rules and regulations of the public entity.

Delegative responsibility refers to a situation in which *entities have a delegated responsibility of most of the decisions on technical operations and asset management but can be corrected by a public authority*. Delegative responsibility refers to the situation of the mining companies in their extraction and storage activities. Extraction and storage plans need to be approved by the ministry of economic affairs a climate policy before the activities can be conducted.

Arbitral responsibility refers to a situation where *entities have their own responsibilities on the decisions on technical operations and asset management of subsystems within the conditions of a public entity that monitors and controls the activities*. An example of conditional responsibility refers to the production of electricity. Or the decentralized production of biogas. The activities are strictly monitored and controlled by an arbitral public body that interferes if an entity is in trespass.

Decentralized responsibility considers a situation where *actors are responsible for the decisions on technical operations and asset management of their own assets and service provision*. Norms and standards still apply, but decisions on technical operations and asset management are fully decentralized. There is no central authority that directly intervenes in the system operations and no authority that directly controls the way the system is designed and operated. Ex ante norms and standards need to safeguard important values as safety and complementarity. The latter is monitored and controlled by public bodies.

### **2.3.3 Categorization of the technical dimension of coordination**

The coordination activities within an energy infrastructure need to be complementary with the allocation of responsibilities to different actors within energy infrastructures. The complexity of the interaction between the nodes and links of the network and the speed with which they need to be coordinated are important drivers for coordination (Scholten & Künneke, 2016).

Public coordination refers to a situation where *all control and intervention tasks are coordinated by a public entity in a top-down fashion*. The transmission system operator coordinates all the system activities regarding transmission. Actors are managed in a centralized way. The development and operation of the energy infrastructure are also controlled from the public entity. Hence, the TSO has the authority to intervene throughout the entire transmission system under supervision of a regulator.

Decision rights infringement refers to a situation in which *a public entity coordinates the decisions on the technical operations of assets*. An example is that the natural gas storage activities are tightly controlled by the SodM. Decision rights are still with the mining companies, but their choices are coordinated by the ministry through the SodM. Control and intervention tasks are coordinated by SodM.

Conditional coordination refers to a situation in which *entities are coordinated by ex-ante prerequisites to determine whether they can perform certain operational activities*. An example of conditional coordination are the permits that are issued to biogas producers. Control and intervention tasks are with the private entities, but the activities are coordinated by an ex-ante assessment on the competence of an entity.

Incidental coordination refers to *a decentralized organizational structure in which entities coordinate in a bilateral fashion when necessary*. Hence, control and intervention tasks are the responsibility of the

owners of a particular component of the energy infrastructure. Coordination is only needed across borders. Incidental coordination exists for example when a decentralized biogas producer wants to inject the biogas in the national grid.

### **2.3.4 Categorization of the economic-institutional dimension of access**

Focusing on the economic-institutional dimension of energy infrastructures, the regulation of access, responsibilities and coordination shifts from a technical system perspective to a market perspective. The question is merely about which segments of the energy infrastructure can potentially be operated by the market. The idea is that the features of energy infrastructures are inherent to certain market failures. The less the market failures need to be addressed, the more the market can be opened. Access to market activities is categorized in closed access, conditional access, collective access, and open access. Access refers here to the degree to which the market is open to new entrants, and degree to which the market can be competitive and dynamic.

Closed access refers to *a public, monopolistic, tightly regulated and static provision of energy related services*. The state is providing or tightly regulating the provision of an energy related services. An example are the TSOs that are providing the transmission services of natural gas and electricity.

Delegated access refers to *an oligopolistic situation where a relatively small number of large players is providing the energy related services*. Due to relatively high natural entry barriers the energy provision is regulated. An example are the DSOs that are providing the distribution services of natural gas and electricity.

Conditional access refers to *a market where new entrants can enter under certain prerequisites, controlled by a public body*. Such a market is competitive and dynamic but bounded to the physical constraints that are regulated by the public body. An example is the Dutch spot market where licensed shippers can participate in. The shippers trade the volumes of natural gas that are present in the Dutch transmission grid within the regulatory framework of the market.

Open access refers to a situation in which *all actors that are willing to and able to can enter the market*. No significant barriers for entering the market exist and competition law determines how market activities occur. Many different buyers and sellers are active in the market in such a way that no market power can be exercised. There is no need for state intervention since the market safeguards the economic, and social values.

### **2.3.5 Categorization of the economic-institutional dimension of responsibilities**

Responsibilities regarding market transactions refer to ownership and decision rights of the various assets of an energy infrastructure. The way in which the responsibilities are allocated at a specific location and time determines how market activities occur. The goal is to deal with possible market failures, market imperfections, and opportunistic behavior.

Public responsibility refers to a situation in which *the state has all the ownership and decision rights over the provision of an energy related service*. An example are the transmission and distribution operators that are publicly owned and operated. They provide the transmission and distribution services.



Public-private responsibility refers to a situation where *ownership and decision rights are allocated through public-private partnerships*. An example is the natural gas extraction by the mining companies that are organized in public-private partnerships regarding the extraction of natural gas.

Monitored responsibility refers to a situation in which *ownership and decision rights are privately allocated but strictly monitored and controlled by a public supervisory body*. An example is the production of electricity in which the independent regulator strictly monitors the production activities of the producers.

Decentralized responsibility refers to a situation where *ownership and decision rights are transacted within the market*. The way the market performs determines how ownership and decision rights are allocated along the several actors within the energy infrastructure. A regulator ensures that no perverse effects are generated by the way the markets works. The boundaries of the market are set by its design (i.e. its formal institutions).

### **2.3.6 Categorization of the economic-institutional dimension of coordination**

Coordination in the energy market is needed in order so safeguard economic efficiency and social values. Different modes of organization are possible, basically varying from vertical integration to private contracting. The question is whether these modes of organization are adequate to safeguard a proper functioning of the market. The coordination layer is therewith considered with the actual organization of the market activities. The layer is categorized in vertical integration, unbundled public coordination, shared coordination, and private contracting.

Public coordination refers to a situation in which *the activities regarding the provision of an energy related service are publicly and centrally coordinated by a public body*. An example of public coordination is the TSO that coordinates the transmission services of natural gas. The transactions in transport capacity are strictly coordinated by GTS.

Public-private coordination refers to a situation in which *the energy related services are coordinated through public-private partnerships*. An example are the extraction and storage plans that need to be approved by the ministry. Decision rights are hence not fully with the mining companies but restricted by a public body.

Conditional coordination refers to a situation in which *coordination on the energy related services is monitored and controlled by a supervisory body based on certain prerequisites*. An example is the coordination over the energy suppliers by the ACM. ACM issues permits to the energy suppliers and monitors and controls their activities.

Decentralized coordination entails *coordination of market activities by the invisible hand of the market*. Competition law should be enough for the market activities to generate economic efficient and societally preferred outcomes. Regulation is needed on the level of formal institutions, that structure the way in which actors interact.

### **2.3.7 Application of the framework**

The application of the comprehensive design framework in the thesis project is based on the application steps described by Scholten & Künneke (2016, p. 17). The application in this thesis project can hence be captured in the following steps:

1. The application of the framework starts with a description of the Dutch natural gas infrastructure. This implies a detailed description of the systemic and institutional environment, the relevant performance criteria of the system, the current technologies and operational practices (i.e. design principles and control mechanisms), and the natural gas-specific governance and modes of organization. The outcome of this step is a clear description of the comprehensive design of the natural gas infrastructure within the concepts of the framework. Based on the comprehensive description, an assessment will be made of the degree of alignment in the current natural gas infrastructure design.
2. The second step of the application is to identify hydrogen infrastructure options that are feasible to be integrated in the Dutch natural gas infrastructure. Once identified, these options will be described in terms of the technologies and operational characteristics that they imply. The outcome are 2 technical hydrogen infrastructure configurations that will be investigated.
3. The third step of the application is to investigate what changes in the natural gas infrastructure design because of the integration of hydrogen. The changes that a hydrogen integration causes will be investigated per hydrogen infrastructure option. This step will be conducted by identifying the elements in the natural gas infrastructure design that need to be added, replaced or adjusted. The outcome of this step is an overview of the change per hydrogen option. Each overview of the hydrogen options represents the implications of its integration for the functioning of the gas infrastructure.
4. The fourth step of the application focusses on the identification and interpretation of these implications. This step considers the problems that occur because of the changes. The focus is on how the other layers of the framework are affected by the changes. The market and operational implications will be identified by analyzing the changes and their consequences. The outcome of this step is a comprehensive overview of the implications per hydrogen option, positioned in the various layers of the framework's dimensions.
5. The last step of the application focusses on the design options to address the implications identified in the previous step. The design options and their trade-offs will be identified. In this step it will be investigated what choices are convenient in the alteration of the current infrastructure design. The outcome is a hydrogen infrastructure configuration that will be discussed along the changes that are needed in the current natural gas infrastructure design.

### **3. The natural gas infrastructure**

This chapter will focus on answering the second sub-research question, *how are the technical system and the market of the Dutch natural gas infrastructure designed and what does this mean for the complementarity within the socio-technical system?* The comprehensive design framework of Scholten & Künneke (2016) is applied to make a description of the Dutch natural gas infrastructure. The design variables in the different layers of abstraction (i.e. access, responsibilities, and coordination) are used to capture and delineate its socio-technical system design. The structured mapping of the technical system and the market, within the boundaries of the framework, allows for an analysis towards their complementarity. The outcome of the technical and market descriptions is used to assess the alignment between technology and institutions in the natural gas infrastructure. Before applying the framework, the general structure and operations of technical system and market will briefly be introduced.

Paragraph 3.1 briefly introduces the regulatory context of the Dutch natural gas infrastructure. Paragraph 3.2 introduces the technical system and describes the present technical system design variables of the natural gas infrastructure. Paragraph 3.3 introduces the market design and describes the present market design variables of the natural gas infrastructure. Paragraph 3.4 provides a discussion on the alignment of the overall system.

#### **3.1 Regulatory context**

Dutch energy legislation is restructured significantly from the European Electricity Directive 96/92/EC and the Gas Directive 98/30/EC. The directives introduced the need to liberalize the electricity and gas sector in all EU member states. The natural gas infrastructure in the Netherlands was historically regulated in a centralized way (Correljé, Linde, & Westerwoudt, 2003). The entire supply chain of natural gas was organized in a vertically integrated monopoly that consisted of a public-private partnership. This public-private partnership consisted for 60 percent of a joint venture, called the Nederlandse Aardolie Maatschappij (NAM). This joint venture consisted of Shell and ExxonMobil (both 30%). The Dutch Ministry was in for the remainder share of 40 percent.

The EU Gas Directive 98/30/EC introduced the need for the Netherlands to liberalize the gas sector, and therewith to unbundle the vertically integrated monopoly. Hence, the EU Gas Directive 98/30/EC was translated in the first Dutch Gas Act in 2000. The Gas Act states the formal framework for a reliable, affordable and acceptable natural gas provision. In principle, it prevents perverse effects from the functioning of the natural gas sector from happening. Regulations on the exploration, storage, and extraction of natural gas were separately formulated into 4 acts until 2002. These acts were replaced by the 2002 Mining act.

In 2003, the EU introduced a second gas directive that replaced the 98/30/EC directive. This 2003/55/EC directive was generally based on the regulation of the transmission, distribution, supply, and storage of natural gas (L. J. de Vries, Correljé, & Knops, 2010). The directive also concerned the use of LNG. The directive recognized the transport and distribution of natural gas as monopoly activities that need to be conducted by appointed system managers (L. J. de Vries et al., 2010). The directive required the access to the storage and LNG facilities to be regulated and allowed the supply of natural gas to take place competitively (L. J. de Vries et al., 2010). Natural gas companies need to keep separate accounts for each of their transmission, distribution, LNG, and storage activities (L. J. de Vries et al., 2010). The separate accounts were aimed to achieve unbundling, enhance competitiveness, and prevent discrimination and cross-subsidization in the natural gas sector. The managers of the distribution

networks, the transmission networks, and LNG facilities are required to provide third party access to their facilities and services (L. J. de Vries et al., 2010). From the directive, the supply of gas to eligible customers is required to be conducted on the bases that all customers are free to choose their supplier.

In April 2009, the EU adopted a new set of directives and regulations to reform the energy sector. These new regulations and directives are referred to as the third EU energy package (L. J. de Vries et al., 2010). The third energy package aims at improving the functioning of the market, strengthening the rights of the consumers, and improving the security of supply as a consequence of potential disruptions (L. J. de Vries et al., 2010). To improve the functioning of the market, the energy package introduced the further unbundling of transmission activities from generation, trade and retail (L. J. de Vries et al., 2010). Additional measures of the package are aimed at providing the market integration between the various EU gas markets. The latter should achieve more economic efficient markets, less market power, and an enhanced security of supply (L. J. de Vries et al., 2010). A key goal of the third energy package was to remove the strategic advantage that the transmission system operators, as vertically integrated monopolies, had because of the involvement in production and trade activities (L. J. de Vries et al., 2010). Another important requirement was the establishment of a national regulator which needed to adhere to a minimum of specified functions (L. J. de Vries et al., 2010). The rights of the consumers are hence protected more strictly by the third energy package.

### **3.1.1 Energy codes**

The energy codes consist of the further specifications of the regulations on the provision of energy. These infrastructure specific codes apply to all the actors that are active within the energy infrastructures. The Gas Act states that the Dutch regulator (i.e. the Authority for Consumers & Markets (ACM)) is responsible for approving the energy codes. These energy codes are composed by the system operators of the transmission and distribution grids, and representatives of the energy markets. The electricity infrastructure and the natural gas infrastructure have separate energy codes.

Basically, the energy codes exist in three distinct categories. First, there are codes that apply to the prices of transmission and distribution. Second, there are codes that apply to the rights and obligations of the system operators and the users of the energy infrastructures. More specifically, the latter category of codes is about the connections of consumers, the allocation of capacity, the metering of energy consumption, the transmission and distribution of energy, and the compensation for failures. Third, there is a collective information code for natural gas and electricity that states which information the different actors may and must share. The Dutch natural gas codes include fifteen distinct energy codes applicable to the functioning of the natural gas infrastructure. These codes include institutional arrangements for the technical, social, and economic functioning of the gas infrastructure, and hence determine how the operational and market activities in the natural gas infrastructure are regulated.

## **3.2 Technical system design**

The Dutch natural gas grid consists of a variety of pipeline networks that are generally categorized into transmission networks and distribution networks. The transmission networks basically connect the natural gas fields with the industry, the power plants, the distribution networks, and neighboring countries. These transmission networks transport natural gas under high-pressure. The Dutch transmission networks are managed and operated by Gasunie Transport Services (GTS), the transmission system operator (TSO). Figure 6 shows a schematic representation of the Dutch transmission grid.

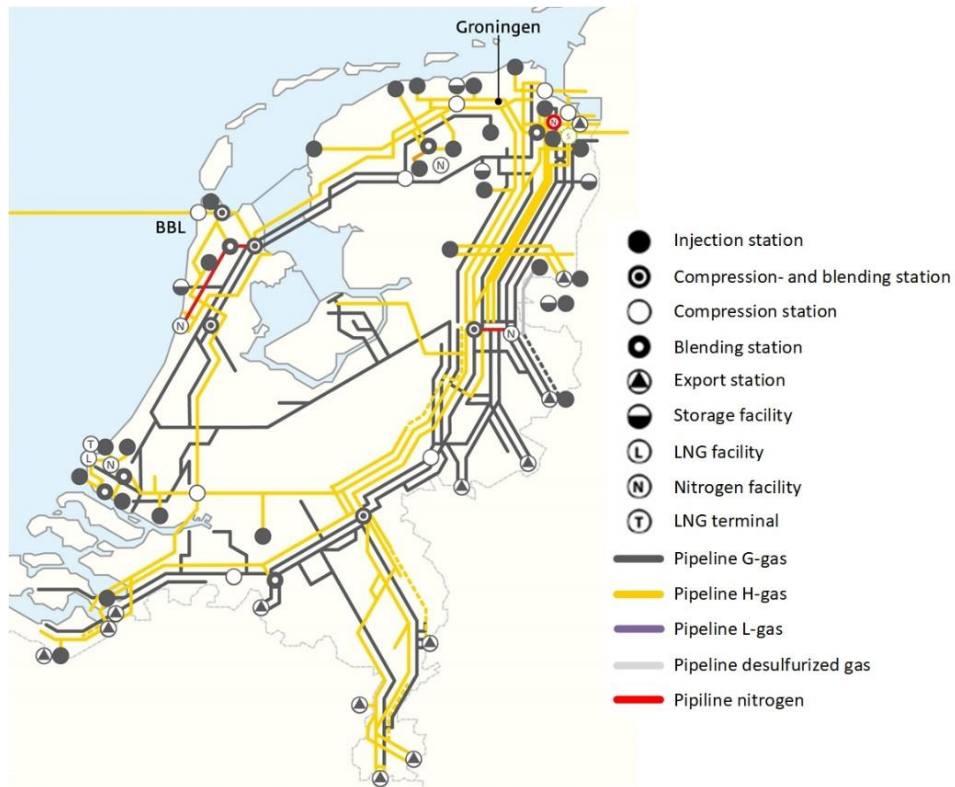


Figure 6: schematic representation Dutch transmission grid, adopted from Gasunie Transport Services (2019)

The distribution networks receive natural gas at specific interconnection points from the transmission networks. The transmission and distribution networks are only connected at these specific interconnection points. The distribution networks are hence distinctive networks managed and operated by several entities. These entities manage and operate a distribution network in a specific area in the Netherlands. Figure 7 illustrates the subdivision of these areas to the several distribution system operators (DSOs). The distribution of natural gas involves the transportation of smaller volumes of gas under lower pressures to a great number of individual consumers (Prieto & Correljé, 2017). In contrast with the larger diameter pipes in the transmission grid, smaller-diameter pipes are generally used in the distribution grid.

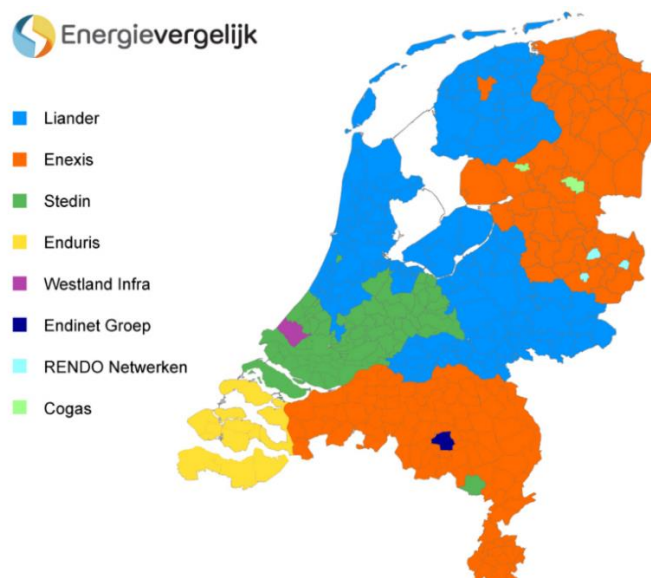


Figure 7: schematic illustration of the DSOs and their operational areas, adopted from Energievergelijk (2018)

The quality of the gas transported in transmission and distribution networks can differ. Gas quality is generally typified by the calorific value of the gas. In the Netherlands, four types of natural gas qualities are distinguished (Gasunie Transport Services, 2019).

1. Groningen gas (G-gas) with a calorific value in between 43.5 and 44.5 MJ/m<sup>3</sup>,
2. High-calorific gas (H-gas) with a calorific value in between 49 and 55.7 MJ/m<sup>3</sup>,
3. Low-calorific gas (L-gas) with a calorific value in between 43.7 and 46 MJ/m<sup>3</sup>,
4. and NGT-gas with a calorific value in between 43.7 and 49 MJ/m<sup>3</sup>.

G-gas is transported in both the transmission and the distribution network. H-gas and L-gas are only transported in parts of the transmission network. NGT-gas is only transported by the part of the transmission grid referred to as the gathering system.

The gathering system connects the natural gas fields with the transmission networks that are compatible with either G-gas, H-gas, or L-gas. The extracted gas is injected into the gathering system in different compositions. This is because of the various natural gas fields that contain a variety of natural gas compositions. The natural gas extracted from the gas fields needs to be processed before it can be injected in the gathering system. This process is referred to as field processing. The natural gas is separated from undesired compounds and dehydrated from undesired liquids. The processing is necessary to adequately transport the natural gas through the gathering system. The undesired vapors and compounds could damage the gathering system and its operations. Table 2 includes the typical composition of natural gas as it is extracted from the natural gas fields.

Compound	Mole Fraction
Methane	0.8407
Ethane	0.0586
Propane	0.0220
i-Butane	0.0035
n-Butane	0.0058
i-Pentane	0.0027
n-Pentane	0.0025
Hexane	0.0028
Heptanes and Heavier	0.0076
Carbon Dioxide	0.0130
Hydrogen Sulfide	0.0063
Nitrogen	0.0345
<b>Total</b>	<b>1.0000</b>

Table 2: Composition of a typical natural gas, adopted from (Guo & Ghalambor, 2005a)

The mole fractions of the components can vary among the gas fields. Methane is the major component of the gas mixture. The inorganic components nitrogen, carbon dioxide, and hydrogen sulfide need to be separated. These components are not combustible and cause corruptions and other problems for the assets of the natural gas infrastructure (Guo & Ghalambor, 2005b). The calorific value of natural gas is dependent on its specific composition. The existence of inorganic components in the gas mixture is a main determinant of the calorific value (Guo & Ghalambor, 2005b). The Dutch Gas Quality Regulation Act states the specific requirements that natural gas needs to have to be transported in the natural gas infrastructure (Ministry of Economic Affairs and Climate Policy, 2014). These requirements include, for example, the minimum and maximum values of molecules and compounds, and consider the limits in calorific value, temperature, and water dew point.

The production of natural gas is conducted by mining companies that extract and process the gas to be injected in the natural gas grid. In the Netherlands, basically three distinct types of natural gas fields are distinguished (L. J. de Vries et al., 2010). First, it is the Groningen gas field that is extraordinarily large. This field produces over 50 percent of the total natural gas extracted in the Netherlands (Centraal Bureau voor Statistiek, 2018; Nederlandse Aardolie Maatschappij, 2018). Second, it is the medium-sized on- and offshore fields. And third it is the small on- and offshore fields. The latter two categories provide approximately the same amount of gas as the Groningen field (Centraal Bureau voor Statistiek, 2018; Nederlandse Aardolie Maatschappij, 2018). Less than 1 percent of the produced natural gas is produced from alternative sources as biogas, syngas, and power-to-gas (Centraal Bureau voor Statistiek, 2018). The latter category of producers often produces lower volumes of gas that are injected in the regional, lower-pressure, networks of GTS (Gasunie Transport Services, 2014).

The demand for natural gas can be separated in the large-scale consumers (i.e. industry and power plants), intermediate consumers, and the small-scale consumers (i.e. small businesses, the residential and service sector). Large-scale consumers have an annual consumption of gas above ten million cubic meters and a market share of about 45 percent (L. J. de Vries et al., 2010). The intermediate consumers have an annual consumption between 0.17 and 10 million cubic meters and receive their gas from the distribution grids (L. J. de Vries et al., 2010). The small-scale consumers are connected to the distribution grids and receive only G-gas. They have an annual consumption of less than 170 000 cubic meters per year (L. J. de Vries et al., 2010). The end-use application technologies of the small-scale consumers are hence compatible with the gas quality that a consumer receives from its connection to the grid. G-gas is historically the gas quality that is found in most Dutch natural gas fields, mainly because of the extraordinary field in Groningen (Correljé et al., 2003). The distribution grid and the end-use technologies of the small-scale consumers are therewith compatible with the use of G-gas.

The demand from the large-scale consumers is relatively stable throughout the year (L. J. de Vries et al., 2010). The demand of the small-scale consumers is fluctuating per season (Prieto & Correljé, 2017). Generally, the demand of the small-scale consumers is higher in winter due to the increased demand for heat. To compensate for this demand fluctuations, the excess supply delivered during the summer months is stored to be available in winter times.

Natural gas can be stored for an indefinite period of time (Prieto & Correljé, 2017). The storage of natural gas is basically conducted in underground storage vessels. These underground storage vessels refer to depleted gas reservoirs, salt caverns, and aquifers. The natural gas storage facilities are operated by the mining companies and the system operators. They inject and withdraw storage capacity from the natural gas grid.

### **3.2.1.1 Technologies and operational practices**

The transmission and distribution networks utilize different technologies to manage the flow of gas. The transmission grid is basically designed to quickly and efficiently transport the natural gas from the natural gas fields to the consumers (Prieto & Correljé, 2017). The distribution grid is designed to effectively and efficiently transport smaller volumes of gas to many small-consumers. Pressure, gas quality, and gas volume are key factors in the management of a reliable and robust flow of energy through the transportation networks. Controlling the gas pressure in the network is crucial since the pipelines and the accompanying installations of the network are designed to operate under specific gas pressures and gas flow rates. Controlling the gas quality in the networks is important since the materials of the pipelines and the installations are designed to be compatible with certain gas qualities. Deviations in the gas quality can damage the pipelines and the installations and hamper their operations. Controlling

the gas volume in the natural gas grid is essential to keep the natural gas volume in the grid in balance. This balance must be continuously monitored and managed to ensure the proper functioning of the natural gas grid. The system operators ensure that the amount of gas that is injected in the grid is equal to the amount of gas that is withdrawn from the grid.

Different technologies are used in the assets of the natural gas grid to control the pressure of the natural gas in the pipeline networks. Pressure reduction stations are located in between the transmission and distribution grid. These reduction stations are part of the gas delivery stations that form the connection between the transmission and distribution grid. The reduction stations ensure that the pressure is reduced to the level adequate for the distribution grid. Compression stations ensure that the natural gas flow through the pipeline remains pressurized (Prieto & Correljé, 2017). These stations are usually placed at 100 to 200 km intervals (Prieto & Correljé, 2017). The natural gas compression is conducted by either a turbine, a motor, or an engine (Prieto & Correljé, 2017).

To adjust the natural gas quality to the right quality standards of a network, blending stations are used. Blending stations generally ensure that the gas matches the requirements of G-gas (Nederlandse Gasunie, 2019a). Blending stations can increase or decrease the calorific values of natural gas. Usually three blending processes are conducted. First, L-gas is blended with H-gas to obtain G-gas. Second, G-gas is blended with H-gas to increase the calorific value of G-gas. And third, H-gas is blended with nitrogen to obtain G-gas. The G-gas in the distribution grids needs to be odorized for safety purposes. This is conducted at the metering and regulation stations in between the transmission and distribution networks (Gasunie, 2018). In addition to the function of compression, the compression stations can also contain some type of liquid separators to control the quality of the gas in the network (Prieto & Correljé, 2017). These separators consists of filters and scrubbers that separate the unwanted liquids and compounds from the natural gas (Prieto & Correljé, 2017).

To control the volume in the natural gas grid it is important that the gas flow is constantly measured. Metering stations are placed periodically along the transmission pipelines for this purpose (Prieto & Correljé, 2017). These metering stations provide important information to the system operators to track the gas as it is flowing to the natural gas grid (Prieto & Correljé, 2017). Metering stations are also used to constantly monitor the quality of the gas in the system (Gasunie Transport Services, 2018e). Basically, the volume of gas is measured at every entry-point and exit point of the transmission and distribution networks. An entry-point refers to a point in a network where gas enters the network. An exit-points refers to a point in a network where the gas leaves the network. The gas quality is measured further upstream of the gas delivery stations (Gasunie Transport Services, 2018e).

To manage the natural gas that enters and leaves the natural gas grid, sophisticated control systems are used by the system operators. These systems are referred to as Supervisory Control and Data Acquisition (SCADA) systems (Prieto & Correljé, 2017). These systems measure and collect real-time data from the pipeline networks and submit it to a centralized control station. Measurement data contains usually the gas flow rate, the operational status, and the gas pressure and temperature (Prieto & Correljé, 2017). These SCADA systems incorporate the ability to remotely control the installations along the pipeline networks (Prieto & Correljé, 2017). The latter function is essential to immediately and easily adjust the flow rates in the pipe.

To control the physical flow of natural gas through the networks, the network includes a great number of valve stations (Prieto & Correljé, 2017). These valve stations work as physical gateways that can be open or closed to control the flow of natural gas through the network. These valve stations can be utilized



to restrict or allow the gas to flow in specific parts of the networks. The system operators remotely operate these valve stations. Intelligent robotic devices, referred to as smart pigs, are used to test the pipe thickness and roundness, to check for corrosion signs, to detect leakages, and to identify any other defect (Prieto & Correljé, 2017). Next to the smart pigs, the system operators know a variety of technologies and procedures to ensure an efficient and safe flow of gas.

The storage of natural gas provides two essential functions for the operation of the natural gas grid. First, it ensures the flexibility of the natural gas supply needed to meet the shifting demands of consumers. And second, it provides the natural gas supply with the needed flexibility to adapt to unforeseen occurrences or disruptions in the production or supply of natural gas. These functions refer to two basic categories of natural gas storage. First, Base load storage, that is used to meet the seasonal demand shifts. And second, peak load storage, that is used to meet short-term, sudden demand increases. Base load storage is usually based on the storage of natural gas in depleted gas reservoirs (Prieto & Correljé, 2017). These reservoirs have large capacities, but relatively low delivery rates (Prieto & Correljé, 2017). The storage facilities therewith function with a steady, prolonged supply of gas. Peak load facilities are usually based on the storage of gas in salt caverns and aquifers. The latter storage facilities hold smaller amounts of gas compared to base load facilities, but deliver small amounts more quickly and can be replenished in a shorter time period (Prieto & Correljé, 2017). Natural gas can also be store in liquid form (i.e. LNG) under high-pressure and low temperatures. The volume of LNG is approximately one over 600 hundred of the natural gas at standard pressure and temperature.

In analogy with the extraction of natural gas, higher pressures in the underground storage facilities will lead to higher gas delivery rates. If the pressure in the storage facilities is lower than the pressure at the wellhead, no pressure difference will push the natural gas outside of the storage facility. Underground Storage facilities hence have amounts of gas that are unrecoverable, referred to as the physical unrecoverable amount of gas (Prieto & Correljé, 2017). To provide the required pressure to ensure the adequate pressure differences, storage facilities include base gas (Prieto & Correljé, 2017). Base gas refers to the amount of gas that needs to stay within the storage facility to provide the required pressure (Prieto & Correljé, 2017). The capacity of the storage facility is referred to as the working gas (Prieto & Correljé, 2017). This is the amount of gas that can be extracted and stored under the normal operation of the storage facilities (Prieto & Correljé, 2017).

### **3.2.2 Access: design perspectives of the systemic environment**

The design perspectives of the systemic environment relate to the generic design of energy infrastructures (Scholten & Künneke, 2016). These perspectives concern the fundamental choices on the system architecture and its asset characteristics. The system architecture concerns the overall shape of the system, its attributes, and how the parts interact (Taft, 2018). Asset characteristics refer to the production, transport, storage, and application technologies that make up the infrastructure (Scholten & Künneke, 2016). Figure 8 shows the position of the access layer in the four layers of system design variables which are referred to as design perspectives. This section will elaborate on the design of the layer's specific variables in the natural gas infrastructure.

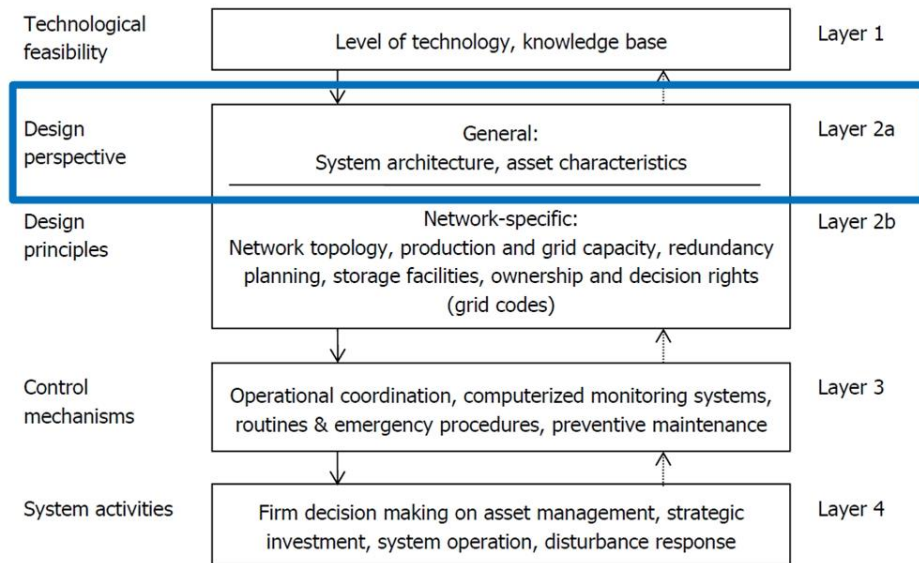


Figure 8: Layer 2a of system design variables in energy infrastructures, adopted from Scholten & Künneke (2016, p. 10)

### 3.2.2.1 System architecture

The technical infrastructure of the natural gas infrastructure basically consists of a production, transportation, storage, and consumption segment. The production segment is historically, as a consequence of the abundant natural gas resources available in the Netherlands, organized in a centralized way (Correljé et al., 2003). The production segment is open to mining companies under the approval of the Dutch ministry of Economic Affairs and Climate Policy. Mining companies are obliged to form a public-private partnership with Energie Beheer Nederland (EBN), i.e. an executive body of the ministry. The mining companies extract an amount of natural gas under the approval of the Dutch Ministry of Economic Affairs and Climate Policy.

The transportation segment of the natural gas infrastructure is designed to transport the centralized produced natural gas from the natural gas fields to the areas of demand. The transmission and distribution grids are owned and operated by public authorities. The transmission and distribution activities are hence closed to participate in. The transmission grid is owned and operated by Gasunie Transport Services (GTS), i.e. the transmission system operator (TSO). The distribution grids are owned by the Distribution system operators (DSOs) as stated in the Dutch energy codes. The DSOs are Coteq Netbeheer, Enduris, Enexis, Liander, Rendo, Stedin Netbeheer, and Westland Infra Netbeheer. The transport capacity can only be used by shippers<sup>2</sup> under the strict regulations of the TSO and the DSOs. The technical system architecture of the transportation infrastructure is hence characterized by centralized hubs (i.e. the system operators) that monitor and control the critical technical functions. The management of the flow of natural gas is based on the day-ahead programs of the shippers. The relations between the nodes and links of the network are hence pre-determined and a priori planned. Interventions in the operation of the network are conducted under directed intervention efforts by the system operators.

Producers, customers, and storage facilitators are connected to the transportation networks via grid connections. These connections are operated and managed by the system operators of a specific network. Besides these connections, no gas flows in and outside the system. Customers and producers of natural

<sup>2</sup> A shipper refers to any energy company that is licensed by GTS to trade natural gas and transportation capacity.

gas can access the natural gas grid within the technical and institutional boundaries of their connection. Storage operators need, in a similar fashion as with the extraction, the approval of the ministry to operate a storage facility. Storage operators transfer gas in and outside of their facilities, based on the physical constraints and the institutional arrangements regarding their facility.

### 3.2.2.2 Asset characteristics

Production technologies are based on the extraction and processing of natural gas that is available in the Netherlands. Natural gas processing refers to the dehydration and separation processes that are needed to make the natural gas compatible for the transport in the transportation infrastructure. The natural gas transportation infrastructure is hence designed to function under specific environmental and gas characteristics. The design of the assets in the Dutch transmission grid follows a categorization of the various pipeline networks into a high-pressure grid (HTG) and a regional, intermediate-pressure grid (RTG). These grids include distinctive basic design perspectives on the asset characteristics of the transportation assets. The end-use applications at large-scale consumers and the storage facilities are designed to be compatible with the specific characteristics of their grid connection. The small-scale consumers have end-use applications that are compatible with the use of G-gas. The gas qualities of G-gas, H-gas, and L-gas are strictly regulated in the Dutch regulation on the gas quality, i.e. WJZ/13196684. Table 3 includes the specific gas qualities of G-gas, H-gas, and L-gas that are applicable to the Dutch natural gas infrastructure. Variations in these values can occur at specific connections but are highly regulated by the system operators.

Transmission grid – Injection and delivery at grid connections		H-gas	G-gas	L-gas
Requirement	[unit]	[minimal-maximal]		
Calorific value	MJ/m <sup>3</sup>	47 – 55.7	43,46 – 44,41	42,7 – 46,9
Higher hydrocarbons	mol%	-	≤ 5	
Water dew point (transmission) at 70 bar	°C	≤ -8	≤ -8	≤ -8
Water dew point (distribution) at 8 bar	°C	-	≤ -10	-
Gas condensate at -3 °C	mg/m <sup>3</sup>	≤ 5	≤ 80	≤ 80
Temperature (transmission)	°C	5 – 30	5 – 30	0 – 40
Temperature (distribution)	°C	-	5 – 20	-
O <sup>2</sup> levels (transmission)	mol%	≤ 0,0005 (HTG) and ≤ 0,5 (RTG)	≤ 0,0005 (HTG) and ≤ 0,5 (RTG)	≤ 0,5
O <sup>2</sup> levels (distribution)	mol%	-	≤ 0,5	-
CO <sup>2</sup> levels (transmission)	mol%	≤ 2,5	≤ 3 (HTG) and ≤ 10,3 (RTG)	≤ 3
CO <sup>2</sup> levels (distribution)	mol%	-	≤ 10,3	-
H <sup>2</sup> levels (transmission)	mol%	≤ 0,02	≤ 0,02 (HTG) and ≤ 0,5 (RTG)	-
H <sup>2</sup> levels (distribution)	mol%		≤ 0,5	-
Chlorine levels in organochlorides	mg/m <sup>3</sup>	≤ 5	≤ 5	-
Fluor levels in organofluorides	mg/m <sup>3</sup>	≤ 5	≤ 5	-
CO levels	mg/m <sup>3</sup>	≤ 2900	≤ 2900	-

Pathogenic microbes	#/m <sup>3</sup>	≤ 500	≤ 500	-
Dust particles size above 5 μm	mg/m <sup>3</sup>	≤ 100	≤ 100	≤ 100
Sulfur in inorganic compound	mg/m <sup>3</sup>	≤ 5	≤ 5	≤ 5
Sulfur in alkanethiols	mg/m <sup>3</sup>	≤ 6	≤ 6	≤ 6
Peak value total Sulfur (before odorization)	mg/m <sup>3</sup>	≤ 30	≤ 20	≤ 20
Peak value total Sulfur (after odorization)	mg/m <sup>3</sup>	≤ 41	≤ 31	-
THT levels (HTG grid)	mg/m <sup>3</sup>	0	0	0
THT levels (RTG grid)	mg/m <sup>3</sup>	0 / 10 – 40	10 – 40	10 – 40
THT levels (distribution grid)	mg/m <sup>3</sup>	-	10 – 40	-
Silicon in silicon compounds	mg/m <sup>3</sup>	≤ 0,1	≤ 0,1	-

Table 3: Dutch gas quality requirements of H-gas, G-gas, and L-gas

The specific gas qualities are highly related to the asset characteristics of the natural gas infrastructure. On the one hand, natural gas is processed to match the requirements of the specific gas qualities. On the other hand, the asset characteristics are determined by the gas qualities and hence designed to be compatible with the specific requirements as defined above.

These pressure levels in the networks are important for the compatibility of various assets used to control the adequate flow of gas. The maximum allowable pressure in the HTG differs per type of transmission network. Basically, the HTG transmission networks are designed with maximum pressures of 67.2 bar, 71.6 bar, and 80.9 bar (Gasunie Transport Services, 2014). The RTG transmission networks are basically designed with a maximum allowable pressure of 41 bar (Gasunie Transport Services, 2014). The pressure levels in the distribution grids are respectively 8 bar and 100 mbar for the high-pressure and low-pressure sections.

The assets of the networks are compatible with natural gas in specific temperatures. The maximum gas temperature in the HTG transmission grid is 50 °C and the minimum temperature is 0 °C (Gasunie Transport Services, 2014). The RTG transmission grid is designed for gas temperatures of 7 °C (Gasunie Transport Services, 2014). Gas colder than 0 °C can cause problems for the coating in the pipelines and gas colder than -10 °C can cause problems for the steel pipes (Gasunie Transport Services, 2014). The system is generally designed for an injection temperature of 7 °C (Gasunie Transport Services, 2014). Variations of injection temperatures occur within the boundaries of 0 to 40 °C (Gasunie Transport Services, 2014). The system is designed for a minimum ambient temperature of -17°C and a minimum soil temperature of 5 °C (Gasunie Transport Services, 2014).

To ensure the adequate inner and nominal diameter of the pipelines, GTS uses fixed combinations of nominal diameters, pressures, and inner diameters. Table 4 illustrates the design perspective of the nominal diameter, pressure, and inner diameter of the pipelines in the various HTG and RTG transmission networks. The networks and their installations are designed for an operating gas flow rate of 20 m/s (Gasunie Transport Services, 2014).

Nominal diameter [mm]	Nominal diameter [inch]	Inner diameter [mm]		
		41 bar (RTG)	67,2 bar (HTG)	80,9 bar (HTG)
100	4	104.7	105	105
150	6	158.7	159	156

200	8	206.5	207	207
250	10	260.5	258	258
300	12	309.7	314	312
400	16	389.0	394	393
450	18	-	444	443
500	20	-	494	492
600	24	-	595	591
750	30	-	745	742
900	36	-	894	890
1050	42	-	1044	1039
1200	48	-	1192	1187

Table 4: Relationship nominal diameter and inner diameter in Dutch transmission pipe design, adopted from Gasunie Transport Services (2014, p. 19)

### 3.2.3 Responsibilities: Network-specific design principles

The responsibilities layer refers to the network-specific design principles on how the overall robustness of the system is ensured and on how the system deals with eventualities. Key are the infrastructure design principles regarding network topology, production and grid capacity, redundancy planning, and storage facilities. In addition to the design principles, ownership and decision rights are allocated to various actors to ensure the robust and reliable flow of gas. These ownership and decision rights include the activities regarding the planning, development, operations, and maintenance of the assets in the system. Ownership and decision rights are also allocated to act in cases of emergency. Figure 9 shows the position of the responsibilities layer in the four layers of system design variables which are referred to as design principles. This section will elaborate on the design of the layer's specific variables in the natural gas infrastructure.

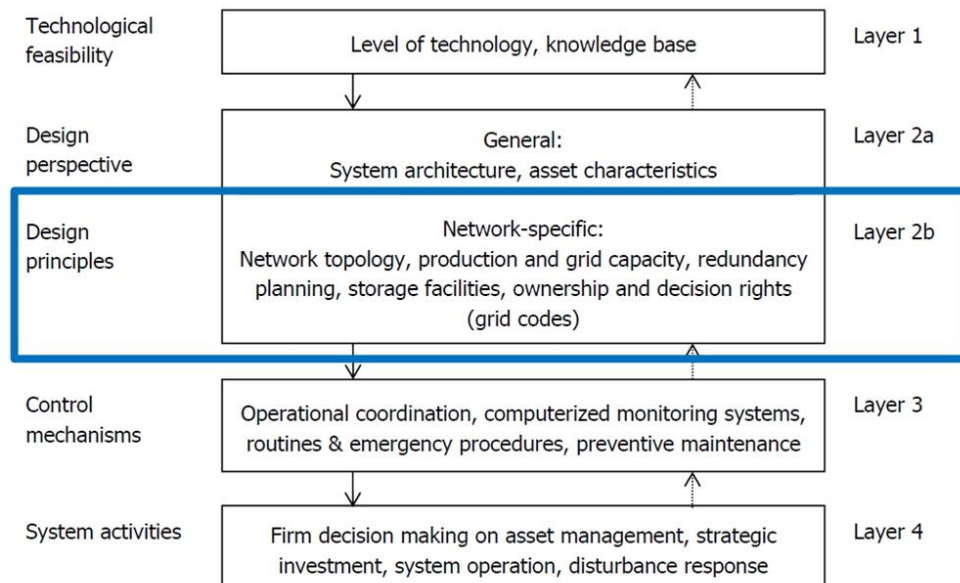


Figure 9: Layer 2b of system design variables in energy infrastructures, adopted from Scholten & Künneke (2016, p. 10)

#### 3.2.3.1 Network topology

The basic physical relations between the components of the natural gas infrastructure (i.e. the nodes and links) refer to its network topology. The network topology is based on the functions of the transmission, distribution, and gathering networks. The assets that facilitate the monitoring and management of the gas flow are positioned along the various nodes of the natural gas infrastructure. Figure 10 shows a basic representation of the network topology of the Dutch natural gas infrastructure. A highly detailed representation of the network topology of the Dutch natural gas transmission grid can be found on the web page of Gasunie Transport Services (Gasunie Transport Services, 2019).

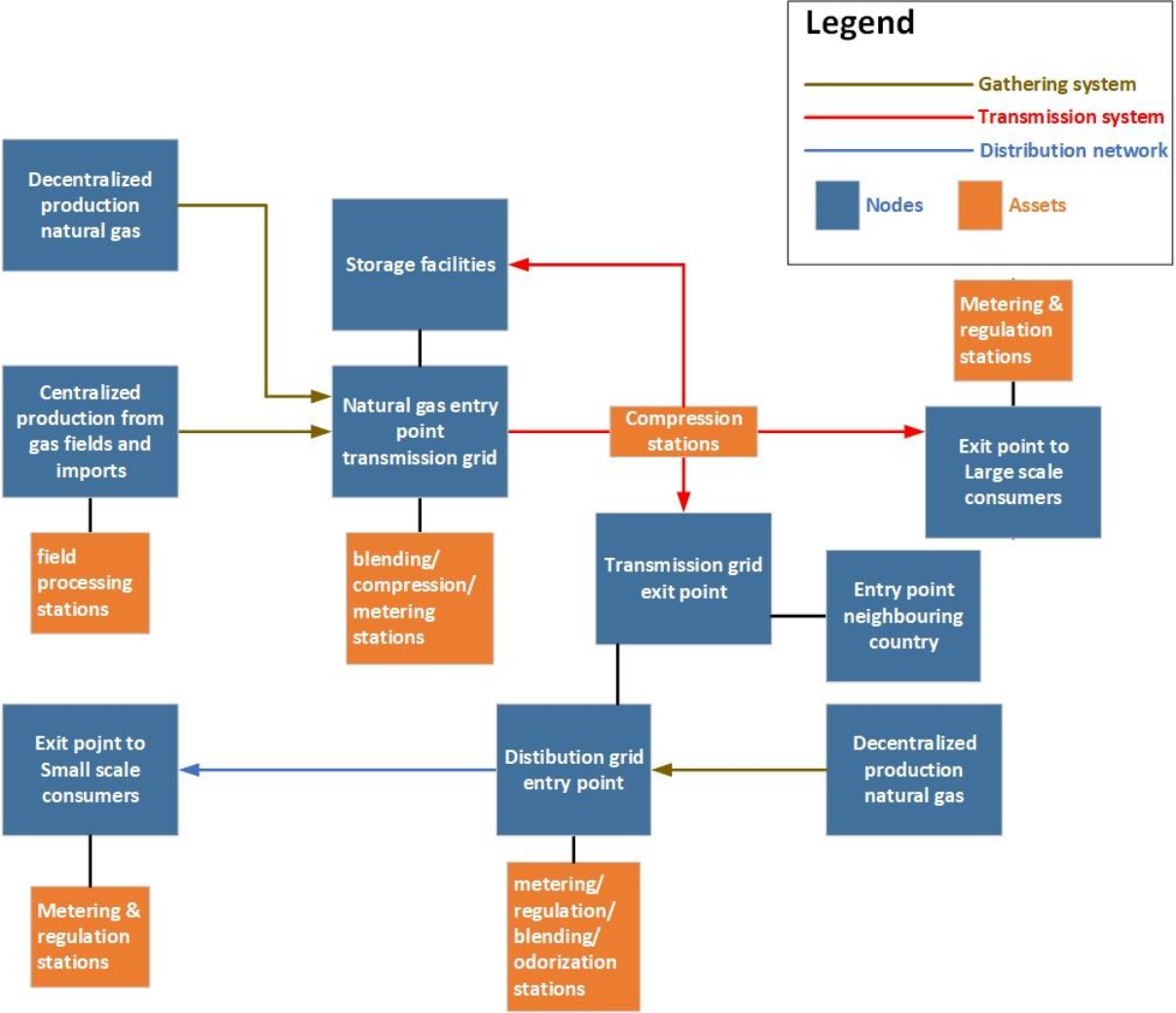


Figure 10: Basic representation of network topology

Natural gas enters the transmission grid at specific physical entry-points. At these entry-points, the volume of the gas entry is measured. The natural gas that is injected at these specific points can originate from storage facilities, the centralized and decentralized production of gas, or gas imports. Before it enters the transmission grid, the gas quality and pressure level will be adjusted to the requirements of the entry-point. Once the gas is present in the transmission grid, the pressure levels are maintained by the compression stations. Through the transmission grid, gas is transported to the specific exit-points in the grid. These exit-points are connected to storage facilities, neighboring countries, large-scale consumers, and the distribution grids. It is ensured that the gas leaves the transmission grid at the right pressure and gas qualities. At these exit-points, the volume of the gas exit is measured. Before the entry-points of the distribution grid, the gas is odorized, and the right gas quality and pressure levels are obtained. The distribution grid transports the gas to its exit-points (i.e. small-scale consumers). The

volume of the gas exit is measured, and it is ensured that the gas arrives at the right pressure and quality. Figure 11 illustrates the topology as described above on the operational level.

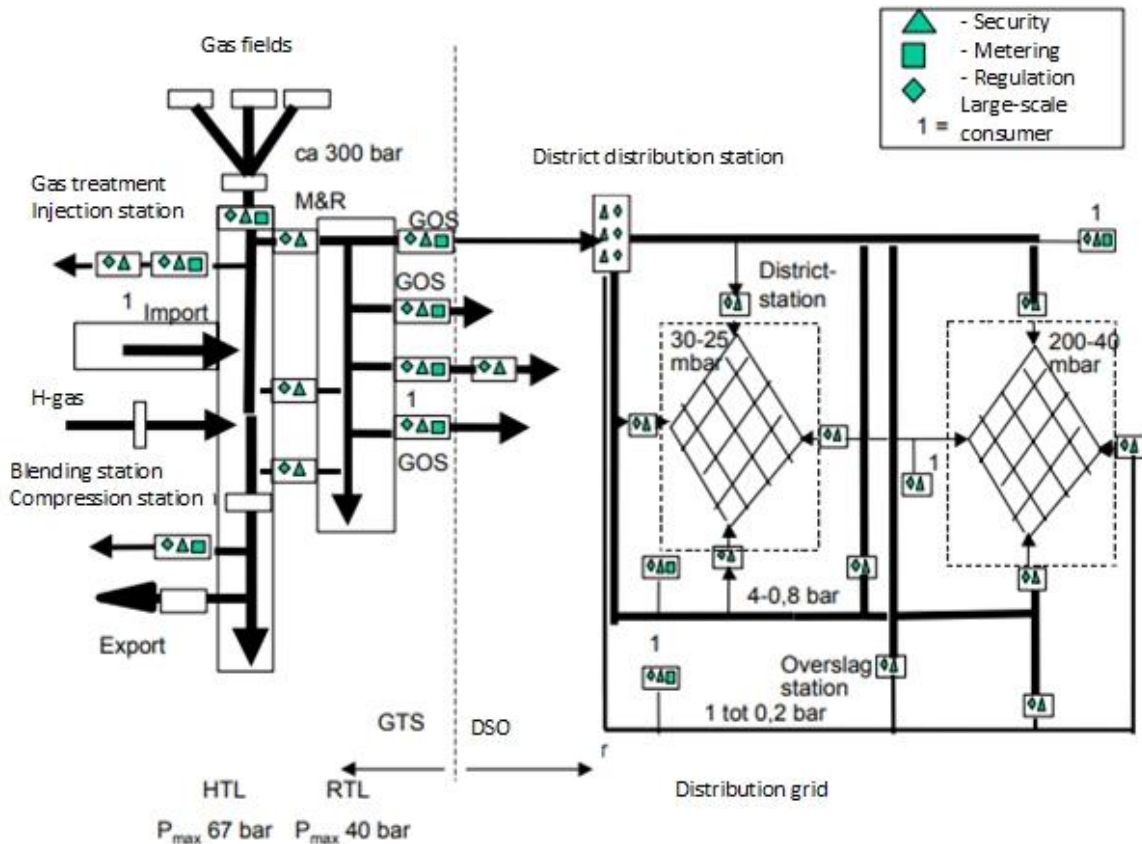


Figure 11: Topology on operational level, adopted from Dienst uitvoering en toezicht Energie (2003)

### 3.2.3.2 Production and grid capacity

The available gas volume capacity in the Netherlands is generally dependent on the Dutch natural gas reserves, the production capacity of the natural gas wells, the import capacity of the interconnection points, and the capacity of the decentralized production of natural gas from other sources. Figure 12 shows the gas reserves in the Netherlands to the left, and the newly discovered and extracted gas reserves to the right. Figure 13 shows the production, imports, and exports of natural gas in the Netherlands from 2010 to 2017.

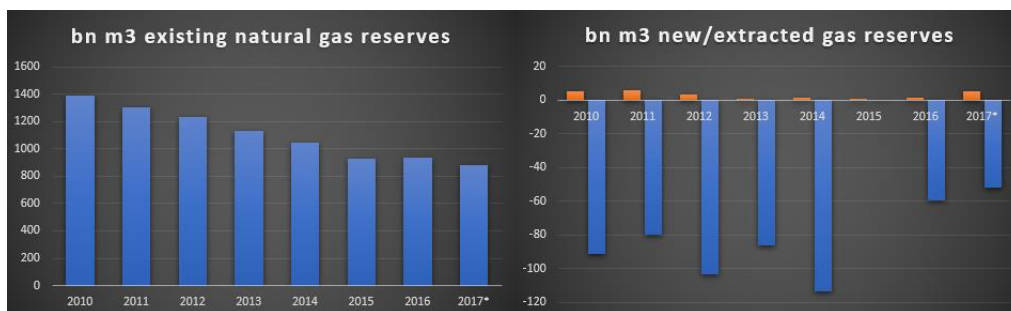


Figure 12: Dutch natural gas reserves, adopted from CBS StatLine (2018c)



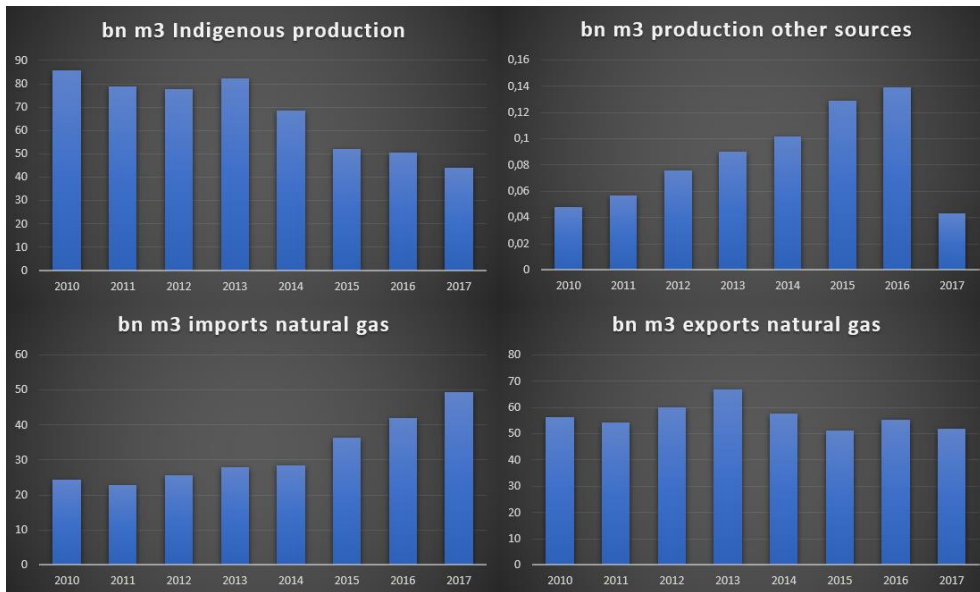


Figure 13: Dutch production, imports, and exports, adopted from CBS StatLine (2018c)

The Dutch natural gas grid is constantly adjusted to meet the changing demands for transportation capacity. Basically, the grid is designed to meet the transportation capacity demand, plus an additional safety range to deal with eventualities. The Gas Act states that the system operators need to prove their capacity adequacy once every two years to the Dutch regulator (i.e. ACM). The capacity of the grid refers to the capacity to adequately transport the natural gas through the grid and the capacity to deliver the natural gas through the various connections with its customers. The transportation capacity of the grid can hence be categorized in base load capacity and peak load capacity. The demand for peak load capacity occurs only occasionally and is legally established in the Gas Act, which is referred to as -17 °C capacity. Base load capacity refers to the normal operational capacity during the various seasons. All entry-points and exit-points in the grid hence have a fixed technical capacity appointed by the system operators. The system operators develop their grids based on the forecasts of the volume demand and capacity demand of its operating area. These forecasts are becoming more important since shippers contract shorter periods of transport capacity (Gasunie Transport Services, 2014). The adequate base load capacity is based on the empirical data on the average historical natural gas consumption. The quality conversion capacity is based on the market demand for conversion. Figure 14 and Figure 15, respectively, show Dutch forecasts of Gasunie Transport Services (2017) in volume demand and capacity demand based on several scenarios for the future.

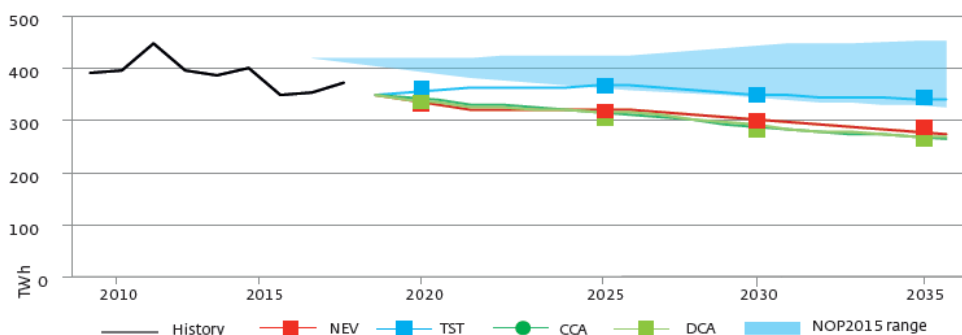


Figure 14: Forecast volume demand, adopted from Gasunie Transport Services (2017)



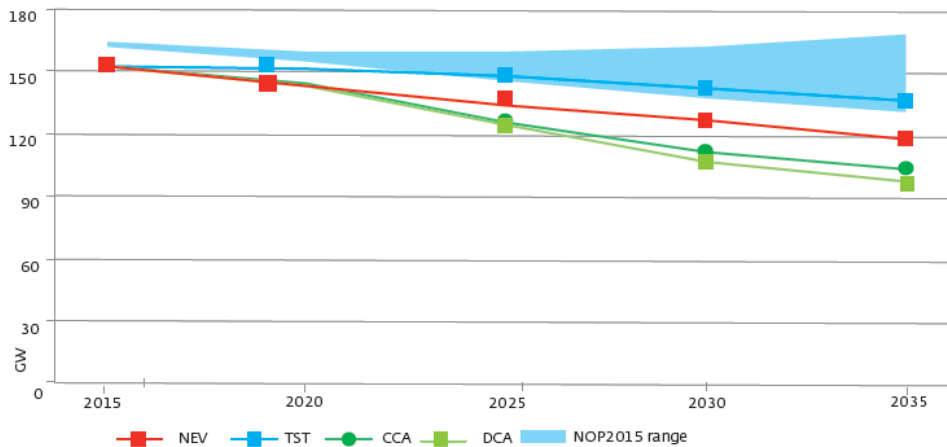


Figure 15: forecast capacity demand, Gasunie Transport Services (2017)

Next to the development of an adequate amount of transportation capacity, the system operators need to constantly monitor and manage the use of the transportation capacity of their grids. GTS checks if the balance of the Dutch grid is maintained and if the shippers are hence not in trespass. The system operators identify the possible transportation scenarios based on the capacity bookings. The system operators are using simulation models for the calculations of the gas flow. The main model used for the capacity planning process of GTS is called Multi Case Approach (MCA) (Gasunie Transport Services, 2014). This model allows for the identification of possible transport scenarios within the physical constraints of the natural gas grid (Gasunie Transport Services, 2014). Other components that are used in the capacity planning calculations are case stationary capacity calculations and a graphical topological interface (GTI) model. The transportation capacity planning calculations of a single-case situation consist of the planning relevant parameters such as gas flow rate, pressure, temperature, and gas quality. The aggregate of the situations is calculated and assessed by GTS using the MCA model.

### 3.2.3.3 Redundancy planning

The Dutch natural gas grid consists of assets that can be categorized in compression stations, blending stations, reduction stations, injection stations, metering stations, and valve stations. Basically, all these assets are over dimensioned based on the theoretical possible conditions. Compression stations follow a N+1 redundancy criterion for all its critical components (Gasunie Transport Services, 2014). The system hence always continues to function since a spare part can replace the broken parts of the compression stations. Moreover, the compression stations in the G-gas and H-gas networks follow the principle of N+1 unit. This means that there is always an extra compression unit available. The blending stations are designed with redundant pipeline meters. These redundant pipeline systems have the function to prevent gas with the wrong quality from entering the natural gas grid. The scrubbers that are used in the compression and blending stations of the H-gas and G-gas networks are also designed on the bases of N+1. Every compression and blending station in these networks have a spare scrubber. The reduction, metering and injection stations are also designed on the bases of the N+1 principle. For every station there is a spare unit available.

### 3.2.3.4 Storage facilities

Natural gas is stored in underground natural gas storage facilities and in LNG storage facilities. The total storage capacity in the large-scale facilities of the Netherlands is approximately 14 billion cubic meters (Energy Stock, 2019; International energy agency, 2008; NAM, 2019; TAQA Energy, 2019). Table 5 shows an overview of the large underground storage facilities and the LNG installations and their basic properties.

Storage Facility	Operator	Type	Capacity working gas (MM m3)	Peak extraction (M m3 daily)	Peak injection (M m3 daily)
Grijpskerk	NAM	Depleted gas reservoir	2000	61	16
Norg (Langelo)	NAM	Depleted gas reservoir	7000	96	45
Maasvlakte	Gasunie	LNG peak-shaving	78	31	0,25
Alkmaar	TAQA Energy	Depleted gas reservoir	500	36	3,6
Bergermeer	TAQA Energy	Depleted gas reservoir	4100	-	-
Zuidwending	Energy Stock (Gasunie)	Salt cavern	310	43,2	26,4

Table 5: overview large-scale gas storage facilities, adopted from International energy agency (2008)

The storage facilities are basically designed to be competitive with the gas prices in the market. Figure 16 shows the annual gas extraction and injection of natural gas in the Netherlands from 2010 to 2017.

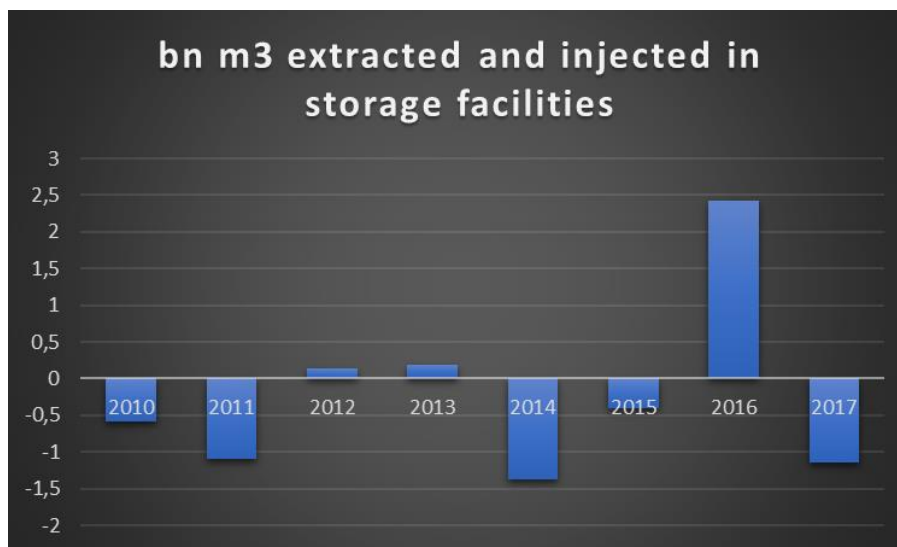


Figure 16: Extraction and injection Dutch storage facilities, adopted from CBS StatLine (2018c)

### 3.2.3.5 Ownership and decision rights

The allocation of ownership and decision rights regarding the assets of the natural gas infrastructure is an important determinant in the way an energy infrastructure is operated. These ownership and decision rights determine the operational responsibilities of the various actors active in the natural gas infrastructure and their operational interrelations. The operational activities within the natural gas infrastructure are mainly regulated by the Gas Act, the Mining Act, and the energy codes. The latter laws and regulations form, together with the various other applicable laws and regulations, the regulatory framework that shapes the operational activities.

The production segment of the natural gas infrastructure generally consists of the natural gas fields, the well heads, the gathering systems, and the processing plants. The natural gas fields are owned by public-private partnerships between the mining companies and the Ministry of Economic Affairs and Climate Policy (i.e. EBN). The mining companies are planning the actual exploitation of the natural gas fields and submit an extraction plan to the Ministry. These extraction plans include the commencement, duration, manner, annual amount, costs, and risks associated with the extraction of natural gas from a field. The decision rights on the planning of the natural gas extraction and the development of the natural gas fields are hence with the mining companies but under the restriction of the Ministry. The day-to-day decision rights on the production planning, development, and operations are with the mining companies. These companies thus have the decision rights on how to exploit the fields in the boundaries of the extraction plans. The assets regarding the wellheads are fully owned by the mining companies.

The gathering system can be categorized in two different segments. First, is the transmission pipeline system that forms the connection from the natural gas fields to the injection stations of the natural gas grid. And second, is the network that connects injection stations to the transmission grids compositable with H-gas, G-gas and L-gas. The first category are privately owned pipeline transportation networks. Examples of these networks are *Westgastransport* (WGT), *Noordgastransport* (NGT), and *Noordelijke offshore gastransportleiding* (NOGAT). These networks are owned, developed, operated, and maintained by the private companies. The WGT, NGT and NOGAT are respectively owned by NAM, Noordgastransport and NOGAT. Decision rights regarding transport capacities are therewith intertwined with the extraction plans of the connected natural gas fields. The actual decision rights regarding the development, operation, and maintenance of the grids are with the private companies. The second category of gathering systems refers to the part of the transmission network that transports the gas with NGT-quality (i.e. calorific value of 44.4 – 49 MJ/m<sup>3</sup>) to the H-gas, G-gas, and L-gas networks of GTS. The latter networks are owned, developed, operated, and maintained by GTS. Decision rights are therewith fully with GTS under the supervision of the regulator (i.e. ACM).

The natural gas processing plants are located in between the natural gas fields and the injection stations. The companies who own the gathering systems often also own the processing plants. They are hence providing processing services to the mining companies. The natural gas processing plants are developed, operated, and maintained by the system operators. The natural gas processing needs to abide by the strict requirements of the injection station that the gas is to be injected in. The injection stations are owned and operated by GTS.

The transmission segment exists out of the following asset categories: pipelines, injection stations, metering stations, pressure reduction stations, compression stations, blending stations, odorization stations, and extraction stations. These asset categories can be physically combined at a specific location in the monitoring and management of the gas quality and gas flow in the Dutch transmission grid. The ownership rights of the pipelines and the various stations are fully with GTS. The same applies to the decision rights on the planning, development, maintenance, and operation of the assets. GTS plans a priori how the different assets are managed to function together to achieve a reliable and robust operation of the system. GTS continuously manages and monitors the gas quality and gas flow. Decision rights regarding the grid connections and the accompanying volumes and qualities are therewith fully with GTS. In the transmission service provision, GTS needs to abide by the strict rules and regulations regarding the public service obligation, safety, and capacity adequacy requirements. The latter is monitored and supervised by the ACM. The right to use the capacity of the transmission grid can be bought from GTS by the various shippers. GTS has the authority to intervene in case of eventualities.

The ownership and decision rights in the storage segment are like those of the production segment. The main difference is that natural gas is also extracted from the grid and injected in an underground storage facility. The assets of the storage segment basically consist of the underground storage facility, and the pipeline system that connects the facility with the gas grid. The underground gas storage facilities and pipeline systems are fully owned by the Dutch storage system operators, see Table 5. The decision rights regarding the planning, development, maintenance and operations of the storage facilities and the pipelines systems are with these storage system operators. The decision rights, in analogy with the extraction plans described above, are constrained by a storage plan. The mining act states the strict regulations on the storage of natural gas. The storage plan, submitted by the storage operator, needs to be approved by the ministry.

The distribution grids operate at different operational circumstances and hence have slightly different asset characteristics than the transmission grid. The assets that make up the distribution grid consist of similar asset categories as the transmission grid. The distribution grid includes pipelines, injection stations, pressure reduction stations, compression stations, metering stations, and extraction stations (i.e. grid connections). The ownership rights of these assets are fully with the Dutch DSOs. The same applies to the decision rights on the planning, development, maintenance, and operation of these assets. DSOs also have a public service obligation, which is much more extensive, since more than 99.9 percent of the total grid connections are on the level of the distribution grids (Netbeheer Nederland, 2018). The right to use the distribution grid capacity is arranged through agreements between the supply companies and the DSOs. The DSOs are responsible for establishing the grid connections with the customers of the supply companies. The decision rights on the operations of the distribution grid and the grid connections are hence with the DSO. The DSO can intervene in case of eventualities.

The end-use segment of the transmission grid consists of a variety of end-use application in the industry and the power generation sector. The end-use segment of the distribution grid consists of a variety of end-use applications to provide the heat demand of the residential sector and other small-scale consumers. The end-use applications of both grids are generally privately owned. Ownership rights can also be rented or collectively divided. Decision rights on the development, operation, planning, and maintenance are with the owners but strictly regulated by norms and standards.

### **3.2.4 Coordination: Control mechanisms**

The coordination layer of the comprehensive design framework refers to the nature of the interaction among actors that are involved in the operational activities in of the natural gas infrastructure. Control mechanisms are in place to ensure the reliable operations of the technical infrastructure. Control systems are hence used to coordinate the flow of natural gas through the complex production, transmission, and distribution systems of the natural gas infrastructure (Scholten & Künneke, 2016). Figure 17 shows the position of the coordination layer in the four layers of system design variables which are referred to as the control mechanisms. This section will elaborate on the design of the layer's specific variables in the natural gas infrastructure.

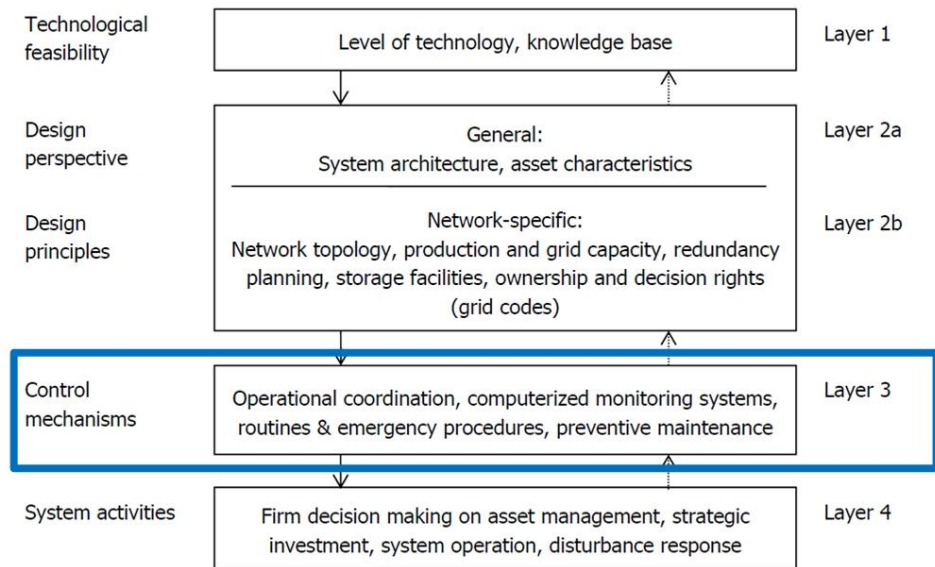


Figure 17: Layer 3 of system design variables in energy infrastructures, adopted from Scholten & Künneke (2016, p. 10)

### 3.2.4.1 Operational coordination and computerized monitoring systems

The production of natural gas from the natural gas fields is controlled by several control mechanisms to ensure the reliable production of gas. These control mechanisms are performed by the mining companies that exploit a natural gas field. Moreover, proper control mechanisms are necessary to establish a reliable gas flow from the natural gas fields. The decision-making on these control mechanisms is regulated through the extraction plans by the ministry (i.e. following the Mining Act). The mining companies hence decide on the specific application of adequate control mechanisms in between the approved boundaries of the ministry. Control mechanisms are hence obligated by the Mining Act. Natural gas processing and blending are used to adequately control the natural gas quality in the various transportation networks.

The important control mechanisms in the production of natural gas are well casing, well completion, preventing well leakage, and well treatment. Well casing is about the strengthening of the drilled well hole by the installation of a series of metal tubes (Prieto & Correljé, 2017). Well casing is a mechanism to strengthen the well hole and prevent unwanted fluids or gases from entering the natural gas flow (Prieto & Correljé, 2017). Well-casing also prevents blow-outs as a result of dangerous pressure levels (Prieto & Correljé, 2017). Well completion concerns the operational decisions on the characteristics of the natural gas production volumes and formations (Prieto & Correljé, 2017). Well completion is utilized to ensure the adequate flow and quality in the production of the natural gas. Different well completion technologies can be applied based on the specific characteristics of the well and the extraction (Prieto & Correljé, 2017). Preventing natural gas leakages from the well is conducted by the installation of a proper wellhead (Prieto & Correljé, 2017). The wellhead basically consists out of three parts, the casing head, the tubing head, and the Christmas tree (Prieto & Correljé, 2017). The casing head provides a seal between the well case (Prieto & Correljé, 2017). The tubing head provides a seal between the tubing heads and the surface (Prieto & Correljé, 2017). The Christmas tree contains tubes and valves to control the flow of natural gas and other extracted fluids from the well (Prieto & Correljé, 2017). Well treatment is another method of ensuring an efficient natural gas production flow out of the well. It is conducted by injecting acid, water, or gasses into the well to open up the formation and allow the natural gas to flow more easily through the well hole (Prieto & Correljé, 2017).

GTS is responsible for the operational balancing, the capacity utilization and allocation, and the controlling and monitoring of the gas flow and quality in the transmission grid. The operational balancing of the natural gas transmission grid is conducted by the utilization of the so-called balancing regime (Gasunie Transport Services, 2018a). Through the application of the balancing regime, GTS ensures that the transmission grid stays in balance (i.e. the exit flows equal the entry flows). Imbalance in the grid is monitored by GTS through the comparison of real-time data with the aggregate of the shippers programs, i.e. the system balance signal (Gasunie Transport Services, 2018a). If the system balance signal is within the acceptable boundaries of the system, the system is conceived to be in balance. When the grid is out of balance, GTS is publishing the system balancing signal on their website. The shippers can hence extract or inject natural gas to restore the balance in the natural gas grid. If the shippers insufficiently restore the balance in the grid, the balance is restored by GTS. The costs of restoring the balance are assigned to the shippers that cause the imbalance. GTS is also applying line packing flexibility services to restore the imbalance in the grid (Gasunie Transport Services, 2018h). Line packing flexibility is applied at the end of a gas day to correct possible imbalances. The coordination mechanism is based on the network buffer capacity (i.e. line packing capacity) of the transmission system (Gasunie Transport Services, 2018h). Instead of restoring the balance of the grid by the injection or extraction of natural gas, GTS is using the buffer function of the grid to restore the imbalance. The parties that cause the imbalance must pay for the line packing flexibility services (Gasunie Transport Services, 2018h).

Next to the balancing regime, GTS is also applying a control mechanism to correct the possible time delays that can exist between the submitted, and actual entry and exit programs of the shippers (Gasunie Transport Services, 2018b). The time delays occur as a result of the buffer effect of the natural gas grid (Gasunie Transport Services, 2018b). The control mechanism is referred to as damping. This mechanism is applied to adequately match the capacity utilization of the grid with the operational limits of the transmission grid. The Damping formula needs to be applied by the shippers that transport gas to the customers of the distribution grid (Gasunie Transport Services, 2018b). The application of the damping formula to their exit programs ensures that the right exit capacity is submitted in their programs. The damping formula is formulated as formulated in Figure 18:

$$E_d(h) = \alpha \cdot Exit(h) + (1 - \alpha) \cdot E_d(h-1)$$

- $E_d(h)$  = damped exit in the current hour
- $Exit(h)$  = exit in the current hour
- $E_d(h-1)$  = damped exit of the last hour
- For first hour of gas day applies:  $E_d(h-1) = Exit(h)$

$$E_{d \text{ \textit{avn}}} (h) = E_d(h) + \frac{\sum_{i=1}^{24} (Exit(h_i) - E_d(h_i))}{24}$$

Figure 18: Damping formula, adopted from Gasunie Transport Services (2018b)

The damping parameter  $\alpha$  is calculated by GTS based on the real-time data on the buffer effect in the grid. If the parameter is changing, GTS publishes the changed parameter on the website. The parameter is hence a control parameter used by GTS to control the way in which the network capacity is utilized and allocated.

The capacity utilization and allocation planning are conducted by GTS. As described in section 3.2.3, various models are used by GTS to plan the capacity utilization of the transmission grid. The physical flow of natural gas is remotely controlled through computerized systems. The continuous measurement of the natural gas grid provides a control mechanism to GTS to adequately operate and manage the transmission grid. All the measurement data is collected in local data acquisition systems managed by GTS (i.e. a supervisory control and data acquisition (SCADA) systems). The data of every connection or interconnection is processed at least once a day by GTS and checked on completeness and correctness. GTS publishes an annual report of the different metering activities and outcomes. The data availability of the metering must comply with an average data availability requirement of 95 percent for the gas quality and 99% for the gas volume (Gasunie Transport Services, 2016, 2018d). The metering activities can also be conducted by a connected party. The prerequisites of third-party metering are that GTS installs the connection and that the gas is extracted for own use. The connected party is obliged to provide the correct measurement data to the local data acquisition system. The data is processed by GTS in the same way as described above.

The control mechanisms in the storage segment are like those applicable in the production of natural gas, as discussed above. The decision-making process on the control mechanism applicable to the reliable flow of natural gas in and out of the storage facility are also regulated by the Mining Act. The difference is that a storage operator needs to submit a storage plan to the ministry instead of an extraction plan. The storage plan contains its own requirements regarding the operations, development, maintenance, and planning of the storage facility. Once approved, the storage plan provides the operational boundaries for the storage operator. In analogy with the extraction plans, the storage plan gives the ministry a means to control the storage of natural gas.

In analogy with GTS in the transmission grid, the DSOs are responsible for the operational balancing, the capacity utilization, and the monitoring and management of the gas flow and quality of the distribution grids. In the distribution grids, there is no transportation capacity of natural gas auctioned. The full transport services and management of the natural gas flow are hence conducted by the DSOs. Capacity is allocated based on the agreement that the DSOs have with the energy suppliers. The consumers that are connected to the distribution grids have agreements with the energy suppliers and use end-use applications that are compatible with G-gas. The latter is ensured to strict norms and standards on the design and installation of the end-use equipment.

#### **3.2.4.2 Preventive maintenance, routines, and emergency procedures**

The preventive maintenance of the natural gas infrastructure includes the regularly testing of the assets and adequate asset management and planning activities. Pipeline networks and their assets are routinely inspected by their operators. The operators routinely apply control mechanisms to ensure the functioning of the natural gas transportation infrastructure. Control mechanisms applied for the detection and prevention of possible damaging circumstances in the pipeline networks generally include the following activities:

- Smart pigging: testing of the pipe thickness, roundness, corrosion, leakages and other defects by smart detection devices (Prieto & Correljé, 2017).
- Patrols: checking if construction activities are not too close to the routes of the pipeline networks (Prieto & Correljé, 2017).
- Leak detection: periodically performed checks on leakages by trained personal on the surface (Prieto & Correljé, 2017).
- Pipeline markers: signs on the surface that indicate the existence of the transportation networks to reduce the change of interference with the pipelines (Prieto & Correljé, 2017).

- Gas sampling: routine sampling of the gas quality to detect corrosion of the pipelines and possible contaminants (Prieto & Correljé, 2017).

The TSO and DSOs have the authority to interrupt the transportation activities in case of emergencies. GTS determines the exact form of the interruption based on the magnitude of the emergency, the geographical location, the speed in which the transportation can be interrupted and restarted, and the consequences of the interruption (Gasunie Transport Services, 2018f). The DSOs follow similar motives for the interruption of the transportation of natural gas.

### 3.3 Market design

The natural gas market consists of a natural gas wholesale market. The natural gas supply in the market is based on the supply that is offered by the various natural gas producers, referred to as the upstream of the natural gas infrastructure (L. J. de Vries et al., 2010). Natural gas in the Netherlands is extracted under concessions which are given by the Ministry of Economic Affairs and Climate Policy (L. J. de Vries et al., 2010). These concessions imply that the state of the Netherlands directly participates as a silent partner in the natural gas revenues for 40 or 50 percent (L. J. de Vries et al., 2010). The amount of gas that can be extracted by the mining companies is therewith largely determined by the Ministry. Mining companies make extraction plans for the extraction from specific fields. These plans need to be approved by the Ministry, prior to the extraction. The natural gas extraction from small natural gas field is generally only economically feasible if a continuous production rate can be established (Knops, de Vries, & Correljé, 2004). The policy of the ministry ensures the continuous production from these smaller fields (Knops et al., 2004). The extraordinary large Groningen field functions more or less as a buffer in the Dutch natural gas supply (Knops et al., 2004).

The supply of natural gas in the Dutch wholesale market is also originating from other countries as Norway, Russia, and Algeria (Knops et al., 2004). This imported gas is traded by a variety of gas traders that mainly import the natural gas through pipelines. Natural gas can also be imported and produced in liquid form and sold in the wholesale market. In the Netherlands natural gas can only be traded in the wholesale market by the so-called shippers<sup>3</sup> (L. J. de Vries et al., 2010). Basically, these shippers buy the gas from the producers and sell it to large-scale consumers and retail companies. To become a shipper, companies must apply for a shipper license. These shipper licenses are managed and approved by GTS. To obtain a shipper license, a company must meet certain requirements that are assessed by GTS. There exist three types of shipper licensees referred to as A-licenses, B-licenses and C-licenses. Basically, all licenses require proof of expertise and financial solvency. The requirements and admission characteristics of the licenses slightly differ. An A-license allows a shipper to trade natural gas and ship it within the Dutch natural gas transmission infrastructure (Gasunie Transport Services, 2018g). Next to the financial and expertise requirements, A-licenses require an extra communication check. B-licenses allow shippers to trade natural gas and ship in within and outside of the boundaries of the Dutch transportation infrastructure (Gasunie Transport Services, 2018g). Shipping the gas outside of the transportation infrastructure refers to the shipping of gas to an exit point. For a B-license, a shipper requires a unique EAN-code and an extra solvency statement (Gasunie Transport Services, 2018g). A C-license only allows a shipper to trade natural gas in the wholesale market (Gasunie Transport Services, 2018g). Shippers include all kinds of companies that are active within the natural gas sector.

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<sup>3</sup> A shipper refers to any energy company that is licensed by GTS to trade natural gas and transportation capacity.



Shippers can be active in the different markets that make up the Dutch wholesale market. The Dutch natural gas wholesale market basically facilitates two separate ways of trading. First, a bilateral market exists where shippers buy the gas from producers and sell it to customers based on bilateral contracts (L. J. de Vries et al., 2010). The customers include large scale consumers as the industry, power plants, and retail companies. The retail companies resell the gas to a variety of smaller-scale consumers connected to the distribution grids. Besides the bilateral trade of natural gas, trade also occurs in the Dutch spot market. The Dutch spot market is basically a virtual market place where gas can be traded. In this virtual market place natural gas can be traded by the hour in an automated fashion with standardized contracts (L. J. de Vries et al., 2010). The virtual market place in the Netherlands is called Title Transfer Facility (TTF). The TTF is operated by GTS and facilitates the trade of natural gas that is present in the Dutch natural gas grid. Only licensed shippers can participate in the TTF. Basically the TTF allows the shippers to trade natural gas as often as they want in between the entry and exit points of the transportation infrastructure (Gasunie Transport Services, 2018m). The TTF is based on the principle that all the natural gas is present in a virtual hub (Gasunie Transport Services, 2018m). Trade hence refers to the transfer of a specific amount of gas from one shipper to the other and virtually happens on the TTF. The actual trading of the gas does not occur on the TTF but on the Dutch gas exchange. The Dutch Ministry of Economic Affairs and Climate Policy assigned the right to function as a gas exchange to ICE ENDEX and ECC B.V. (Gasunie Transport Services, 2018m). When gas is traded, either bilaterally or through a gas exchange, the shippers need to submit the trade to GTS. Such a submission is referred to as a nomination and includes the period of the trade, the amount traded, and the shippers involved (Gasunie Transport Services, 2018m). Shippers with a C-license can only trade natural gas at entry and exit points since they are not allowed to ship the natural gas. Shippers with an A-license or B-license arrange the actual transport and the associated contact with GTS on behalf of the shippers with a C-license (L. J. de Vries et al., 2010). The transport is arranged through the so-called Prisma-platform. On this platform, shippers can book transport capacity on entry and exit points. GTS manages this platform and assigns the booked transport capacity based on its availability and techno-operational feasibility (Gasunie Transport Services, 2018c). The tariffs at every entry and exit points are fixed and determined by the Dutch independent regulator, i.e. the Authority for Consumers and Markets (ACM) (Gasunie Transport Services, 2018c). Entry capacity refers to the right of a shipper to inject a specific amount of gas per hour at a specific entry point (Gasunie Transport Services, 2018c). Exit capacity refers to the right of a shipper to withdrawal a specific amount of gas per hour at a specific exit point (Gasunie Transport Services, 2018c). A shipper can freely choose a combination of entry and exit bookings. The entry and exit contracts of the shippers make up the portfolio of a shipper. A shipper can have several distinctive portfolios (Gasunie Transport Services, 2018c).

Shippers need to contribute to the balancing regime of GTS at all time. This balancing regime requires the entry and exit programs of the shippers to be balanced. The shippers are hence required to ensure that their input of gas into the network and their withdrawal of gas from the network are in balance at any time (L. J. de Vries et al., 2010). This is referred to as program responsibility. The injection and withdrawal plans of the shippers must be submitted on an hourly basis to GTS and are referred to as programs (Gasunie Transport Services, 2018k). The aggregate of all individual programs needs to stay within an acceptable range in terms of the balancing position of the grid. GTS checks if the exit amounts equal the entry amounts. It also checks all the programs on compatibilities regarding the counterparties, volumes, time periods and directions. Basically, shippers have program responsibility of a specific amount of natural gas that is injected in, withdrawn from or transferred within the Dutch natural gas grid. Programs specify the hourly prediction of the day-ahead gas flows in a specific portfolio (Gasunie Transport Services, 2018d). The transfer of program responsibility is, as stated in the Gas Act, conducted at a virtual point in the grid, referred to as the VPPV. All the natural gas in the Dutch natural gas grid is

virtually passing this VPPV. This point is hence a combination of all trades and transfers from the shippers' entry programs to their exit programs. Figure 19 illustrates the entries, exits, and the VPPV.

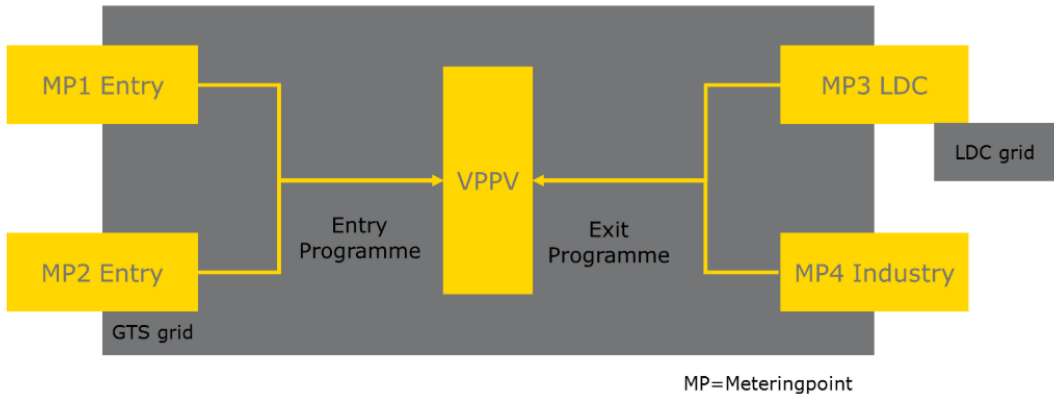


Figure 19: Schematic illustration of the entries, exits, and VPPV, adopted from (Gasunie Transport Services, 2018k)

A distinction is made between trade that includes the physical entry or exit from a shipper's portfolio, and trade that does not. Another distinction is made between entry programs and exit programs. This results in three kinds of programs that need be submitted based on the market behavior of a shipper. First, there are trade programs that include a specification of the totalized trade of a shipper per hour without a physical entry or exit (Gasunie Transport Services, 2018k). Second, there are entry programs that specify the totalized volume of the physical entry in the shipper's portfolio per hour (Gasunie Transport Services, 2018k). And third, there are exit programs that specify the totalized volume of the physical exit in the portfolio of the shipper (Gasunie Transport Services, 2018k). Shippers that are only active on the TTF are obliged to submit a trade program of the sum of their trades (Gasunie Transport Services, 2018k). Shippers that have booked both entry and exit capacity must submit an entry and an exit program (Gasunie Transport Services, 2018k). If these shippers are also active on the TTF, the sum of the trades needs to be included in their entry program. If shippers only book entry or exit capacity, they only submit either an entry or exit program. The sum of their trades needs to be included. The shippers that submit an exit program need to make a distinction between exit flows to the local distribution grids and exit flows to the industry and power plants (Gasunie Transport Services, 2018k). The Dutch spot market provides the reference price of the natural gas in the area. This reference price is based on the supply and demand of natural gas and therewith volatile. The spot market hence provides an adequate means for the gas producers, gas storage operators, retail companies, and consumers to gain financial benefits from anticipated market activities.

The storage of natural gas has, besides its function of ensuring the security of supply, an important commercial function. Natural gas can be stored when prices are low and withdrawn when the prices are high. The business case of natural gas storage facilities is largely based on the costs of storage and the revenues that the storage capacity generates. The costs of a storage facility are dependent on the specific characteristics of a facility. Depleted gas reservoirs include relatively low costs compared to aquifers and salt caverns (Prieto & Correljé, 2017). This is because the underground formation of the depleted reservoirs is geologically already capable of holding natural gas. Moreover, depleted gas reservoirs generally include the extraction and distribution equipment that is needed. Aquifers and salt caverns include much higher costs because of the costs linked to the unknown geological characteristics and capacity (Prieto & Correljé, 2017). Moreover, all the extraction, storage, processing and transportation infrastructure need to be installed. Base gas needs to be bought and injected to provide the operational pressure (Prieto & Correljé, 2017). Salt caverns have, however, the lowest base gas requirements of the

types of underground storage facilities and include higher deliverability rates (Prieto & Correljé, 2017). The economic feasibility of a storage facility is thus largely based on the level of the natural gas prices and the specific characteristics and location of the underground storage facilities.

Producers include a similar business case to that of storage operators. Gas is not stored but only extracted from natural gas fields. The business case of producers is therewith dependent on the costs of the production and transportation of the gas and the natural gas price. Both distribution and transmission operators are not allowed to participate in any commercial activities. The business case of the retail companies is based on the buying and reselling of natural gas on the wholesale market and the costs of transportation.

### 3.3.1 Access: Formal institutions

The access layer of the comprehensive design framework refers to the generic institutional design of the infrastructures (i.e. institutional environment). The institutional environment concerns the formal institutions regarding the polity, judiciary, bureaucracy, and competition law. Polity refers to the general institutions on the way in which the Dutch state is organized. Judiciary refers to the organization of the judicial authorities in the Netherlands, and bureaucracy refers to the general organization of the state officials. The latter three concepts are concerned with the general formal institutional system of a country. The concepts define the institutional system where energy infrastructures exist in. Competition law refers to the institutions that are in place to make sure that fair competition exists between the various market actors. Figure 20 shows the position of the access layer in the four layers of economic institutions which are referred to as formal institutions. This section will elaborate on the design of the layer's specific variables in the natural gas infrastructure.

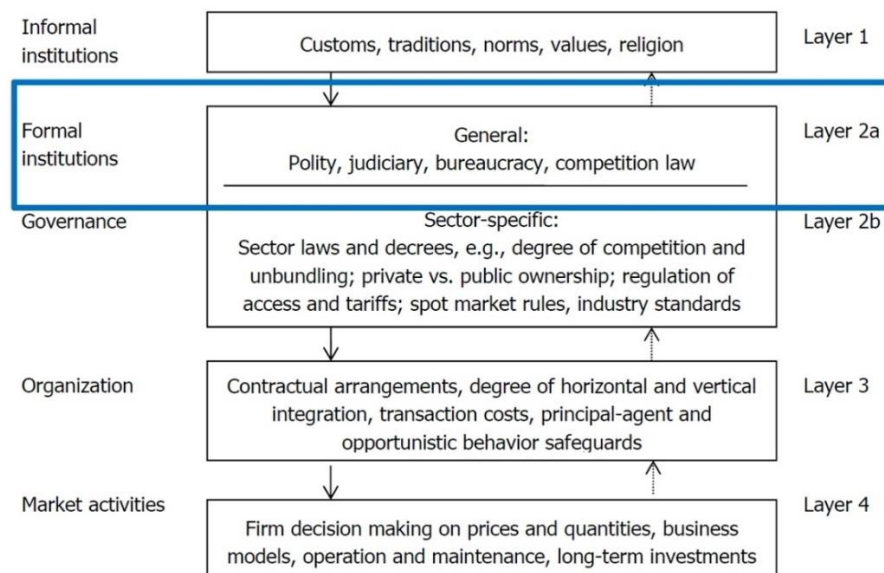


Figure 20: Layer 2a of economic institutions in energy infrastructures, adopted from Scholten & Künneke (2016, p. 12)

#### 3.3.1.1 The Dutch institutional environment

The Dutch state can basically be separated into three branches. The legislative power, the executive power, and the judicial power. The legislative power consists of the parliament and determines the legislation in the Netherlands. The executive power consists of the government and the Ministries. Executive power is also decentralized in the provinces and municipalities. The judicial power controls the application of the laws and regulations. The Dutch institutional environment is much more

comprehensive than this thesis project will address. In the scope of the thesis project, it basically refers to the formal state institutions, and the perceptions on how the energy provision should be performed (Scholten & Künneke, 2016). The institutional environment forms the regulatory framework (i.e. the rules of the game) that constraints the behavior of the various actors within the natural gas infrastructure. In this thesis project, the focus is largely on the specific design of the institutional environment of the natural gas infrastructure. That is, the actual elaboration of the institutional environment in the lower layers of the comprehensive design framework. The institutional environment hence provides the boundaries of what is socially and economically preferred.

### **3.3.1.2 Competition law**

The Dutch competition law is providing a comprehensive regulatory framework for the participants in the various markets in terms of the rules on competition and market mechanisms. Dutch competition law is generally based on the European council regulation (EC) no 1/2003 and council regulation (EC) no 139/2004. Dutch competition law refers to the variety of laws, administrative decrees, ministerial regulations, ministerial policies, and the policies and guidelines of the ACM (ACM, 2018). The Dutch independent regulator (ACM) checks if the competition law is adequately fulfilled. Next to the ‘general institutions’, there exists a variety of sector-specific laws and regulations applicable to the energy sector and the natural gas sector. These sector-specific laws and regulations will be elaborated on in the next section. The production segment of the natural gas infrastructure is open for producers under the strict regulations of the Ministry of Economic Affairs and Climate Policy. The admission to exploit the natural gas field is based on an extraction license provided by the ministry<sup>4</sup>. Competition on the exploitation of the various natural gas fields is thus based on the competition on these licenses. The wholesale market for natural gas is open to the licensed shippers. The wholesale market can be conceived as a competitive market where producers offer their natural gas supply and customers bid for their demand. The bilateral market can also be conceived as a competitive market where bilateral agreements can be freely arranged. The transmission and distribution activities are separated from the market activities in regulated public monopolies. No competition is present within the transmission and distribution activities. The storage operators need a shipper license to trade in the wholesale market. Competition in the admission of operating a storage facility is, in analogy with the extraction of natural gas, based on the license that is needed from the ministry. Large-scale customers need a shipper license and buy the natural gas directly on the wholesale market. The retail market is open for suppliers who have at least a category A-shipper license. The small-scale consumers can openly access the retail market, in which they can choose from various retail suppliers. The transmission capacity is auctioned among the interested shippers. The distribution grid capacity is openly accessible for the small-scale consumers under fixed prices, no distribution capacity auction exists. The distribution capacity is connected to the grid connections of the distribution grid. Retail competition hence exists based on the wholesale market.

### **3.3.2 Responsibilities: Governance**

The responsibilities layer of the comprehensive design framework refers to the market governance arrangements in the natural gas infrastructure (Scholten & Künneke, 2016). The market governance arrangement of the natural gas infrastructure concerns the degree of competition that is allowed, the allocation of ownership and decision rights regarding market activities, and the sector-specific regulation that constraints the actor behavior (Scholten & Künneke, 2016). The degree of competition refers to the possibilities for liberalization, unbundling, and substitution (Scholten & Künneke, 2016). It is about the type of good or service that is sold under specific cost-structures. The position of the good or service regarding the lifecycle of natural gas is an important determinant of the degree of competition

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<sup>4</sup> “The ministry” refers, from now on, to the ministry of Economic Affairs and Climate Policy.

that can be allowed (Scholten & Künneke, 2016). The allocation of ownership and decision rights refers to the allocation of the right to use an asset, the right to own an asset, the right to own the benefits of an asset, and the right to sell an asset to public or private actors (Scholten & Künneke, 2016). Sector-specific regulations refer to the regulations that are in place to address the values formulated in the institutional environment. Basically, the institutional environment is translated in sector-specific regulations that need to achieve a reliable, acceptable, and affordable gas provision. These regulations are, for example, regulations on access and tariffs, spot market rules, and industry standards (Scholten & Künneke, 2016). Figure 20Figure 21 shows the position of the responsibilities layer in the four layers of economic institutions which are referred to as governance arrangements. This section will elaborate on the design of the layer's specific variables in the natural gas infrastructure.

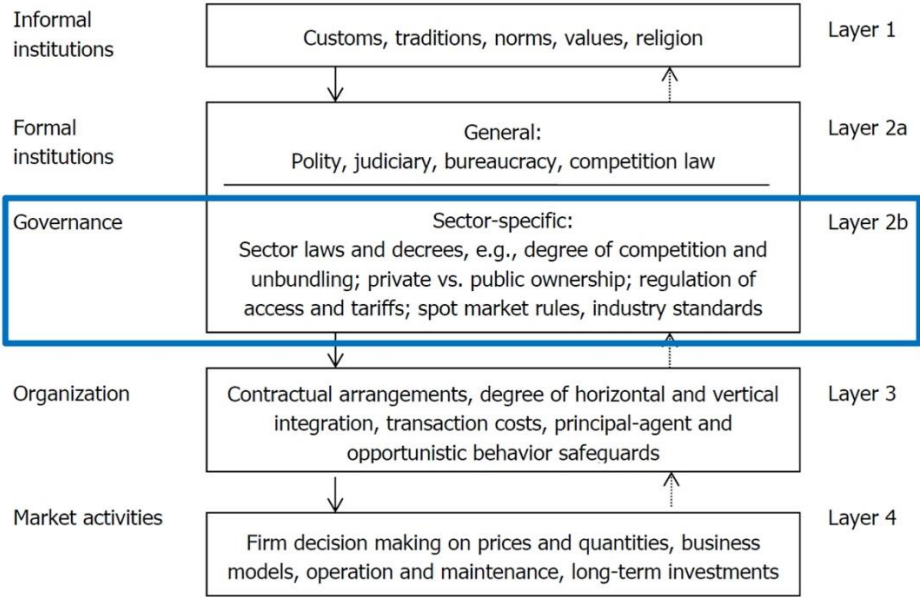


Figure 21: Layer 2b of economic institutions in energy infrastructures, adopted from Scholten & Künneke (2016, p. 12)

**3.3.2.1 Liberalization**

The extraction and storage plans, in combination with the permitting, are in place to control the possible risks of the gas extraction and storage activities. Adequate safety and efficiency measures need to be conducted by the mining companies. The latter is strictly regulated to prevent harm to the environment and the people, and to achieve an efficient natural gas provision. The boundaries of the storage and extraction activities are specified in the extraction and storage plans. These plans are enforced by the State Supervision of Mines (i.e. SodM), an executive body of the ministry. SodM is controlling the activities of the mining companies in terms of safety, health, environment, and efficiency of the operations (State Supervision of Mines, 2018). The Mining Act states the function of the SodM, the permitting procedure, and the procedure of approving the extraction and storage plans. The further liberalization of the production and storage activities is conceived to be undesirable. This would hamper the control on the potential risks of the natural gas production and storage.

GTS controls the access to the wholesale market by the issuing of the shipper licenses. Access should be provided based on fairness and non-discriminatory criteria. The market activities are subject to the market rules that are enforced by GTS and controlled by ACM. The market activities occur in the strict regulations of a transparent, automated and standardized wholesale market. The Dutch wholesale market can be conceived to be competitive.

The retail consumers can choose their retail supplier, but not their distribution system operator. The consumers are bound to a DSO that is assigned by the Energy Codes to the specific area of the gas connection. The retail market is accessible for the retail suppliers by a gas supplier permit. This permit is issued by the ACM and ensures that only financially sound and competent companies can enter the retail market. Further liberalization of the permitting process is conceived to be undesirable since a certain degree of control needs to be established.

### **3.3.2.2 Unbundling**

The unbundling rules of the third energy package focus on the unbundling of the transmission and distribution activities from the production, trade, and supply activities. TSOs cannot be involved in distribution activities and DSOs not in transmission activities. Legal unbundling of a DSO refers to the legal independence of a DSO from any other activities not related to the distribution of natural gas. The same applies for a TSO, which is not allowed to be legally involved in distribution, supply, trade, and production activities. Functional unbundling refers to the independence of the personal working at the system operators. The personal of the TSO is not allowed to be directly or indirectly involved in the day-to-day operation of natural gas supply, production, trade, or distribution activities. The same applies to the DSOs. Companies need to keep separate accounts for each of their transmission and distribution activities. The ACM is controlling if the unbundling rules are fulfilled.

### **3.3.2.3 Substitution**

The utilization of natural gas as an energy carrier for the purpose of heating the residential and service sector is most common. Substitutes that are currently considered to be viable to replace the natural gas condensing boilers are electric heat pumps, district heating connections, and green gas connections. The penetration of these substitutes is rather low. Heat pumps are currently providing 1.2 percent of the total heat demand of the distribution grid connections (CBS StatLine, 2018d). Approximately 5.6 percent of the total distribution grid connections is connected to a district heating grid (CBS StatLine, 2018b). From these distribution grid connections, over 70 percent is still based on the combustion of natural gas (Menkveld, Matton, Segers, Vroom, & Kremer, 2017). Less than 1 percent of the total gas supply to the distribution grid connections is fulfilled using synthetic methane (Centraal Bureau voor Statistiek, 2018). There are a variety of other options to substitute natural gas and the accompanying transmission, distribution, and storage services. LNG is, for example, a substitute for the gaseous natural gas market. Approximately 3 percent of the total Dutch natural gas imports are currently in the form of LNG (Centraal Bureau voor Statistiek, 2018). The electricity prices for heat pump systems in households are currently, assuming an average heat pump COP of 3, competitive with the prices of natural gas. A heat pump COP of 2 to 4, respectively corresponds, with a price difference electricity compared to gas of -0.14 and 0.17 €/kWh energy output (CBS, 2018a). The prices of NUON district heating for households are currently approximately 0.10 €/kWh, the prices for electricity and gas are respectively 0.14 and 0.06 €/kWh (CBS StatLine, 2018a; NUON, 2018).

### **3.3.2.4 The cost-structure of natural gas**

The costs included with the operation, maintenance, development, and planning of the natural gas infrastructure are very extensive. Fixed costs include, for example, the cost that are related to the investments in the various assets of the production, storage, transmission, distribution, and end-use segments of the infrastructure. Variable costs basically include the costs of the operational, maintenance, support services, depreciation, and development of these assets. The natural gas prices hence reflect these costs including a margin for trading. The costs of natural gas can be referred to as the internal price indicators (i.e. directly from the natural gas provision). External price indicators are the price of possible

substitutions throughout the natural gas supply chain. The latter price indicators are complex in nature, and harder to capture. The natural gas price is both determined based on internal and external indicators. Figure 22 illustrates the natural gas pricing structure. In the Netherlands the prices of natural gas are determined by supply and demand (i.e. through the market). The natural gas market is an international market that is hence being influenced by the international energy and feedstock market.

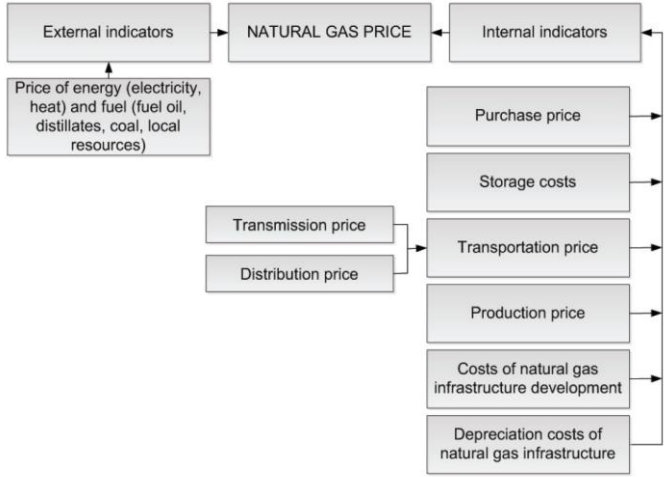


Figure 22: Natural gas pricing structure, adopted from Giziene & Zalgiryte (2015, p. 115)

The end-use price for consumers includes the costs of the whole supply chain. The composition of the residential natural gas price in 2010 excluding taxes, in respectively Italy and France, is illustrated in Figure 23. This structure is referred to as a cost-plus structure. The largest share of the natural price can be dedicated to the production costs (i.e. FOB price). The distribution costs of natural gas are also significantly contributing. The latter two activities represent more than half of the natural gas price excluding taxes.

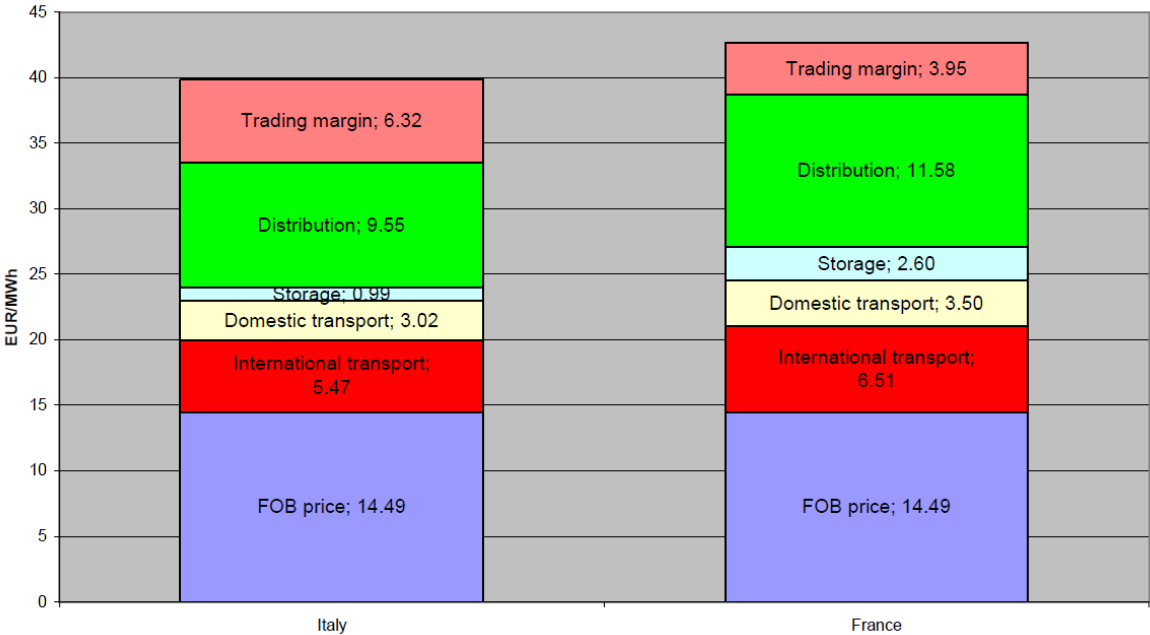


Figure 23: Composition of average residential price, adopted from Prieto & Correljé (2017, p. 46)

In the Netherlands a large share of the price retail price of gas consist of taxes. Table 6 shows the development of the natural gas retail prices and the share of taxes from 2010 to 2017. The first two

columns represent the prices and taxes for the demand categories below 20 GJ and the last two columns, the prices and taxes of the demand category of households in between 20 and 200 GJ.

Year	Transaction price including taxes for annual demand < 20 GJ	Transaction price excluding taxes for annual demand < 20 GJ	Transaction price including taxes for annual demand in between 20 GJ and 200 GJ	Transaction price excluding taxes for annual demand in between 20 GJ and 200 GJ
2010	€ 28,25	€ 19,11	€ 11,64	€ 19,37
2011	€ 29,72	€ 20,31	€ 12,37	€ 20,27
2012	€ 31,14	€ 21,29	€ 13,40	€ 21,71
2013	€ 32,42	€ 21,43	€ 13,36	€ 22,66
2014	€ 33,28	€ 21,99	€ 12,91	€ 22,29
2015	€ 32,38	€ 21,12	€ 12,11	€ 21,48
2016	€ 32,49	€ 19,37	€ 10,63	€ 21,92
2017	€ 34,12	€ 20,56	€ 10,37	€ 21,78
Year	Taxes for annual demand < 20 GJ	Percentage of taxes of total price for annual demand < 20 GJ	Taxes for annual demand in between 20 GJ and 200 GJ	Percentage of taxes of total price for annual demand in between 20 GJ and 200 GJ
2010	€ 9,14	32,4%	€ 7,73	39,9%
2011	€ 9,41	31,6%	€ 7,90	39,0%
2012	€ 9,85	31,6%	€ 8,31	38,3%
2013	€ 10,99	33,9%	€ 9,29	41,0%
2014	€ 11,29	33,9%	€ 9,38	42,1%
2015	€ 11,26	34,8%	€ 9,37	43,6%
2016	€ 13,12	40,4%	€ 11,28	51,5%
2017	€ 13,55	39,7%	€ 11,41	52,4%

Table 6: Dutch Residential gas prices and taxes from 2010 to 2017, adopted from CBS (2018)

### 3.3.2.5 Allocation of ownership and decision rights

The allocation of ownership and decision rights refers to the allocation of property rights among the various actors in the natural gas infrastructure. Different systems of property rights are active (private, public, collective, or common) that influence the behavior of actors. It is important to look at the bundles of property rights that are assigned to the various actors in the natural gas infrastructure. Important questions are hence: What bundles of property rights are assigned to which actor? How does the allocation of property rights affect the economic incentives of actors to act in a certain way? And how does the allocation of property rights incentivizes actors to transact with one another? Vining & Weimer (2016) identify six essential dimensions of property rights that are essential in understanding how property rights are assigned. These dimensions are: fragmentation of ownership, clarity of allocation, costs of alienation, security from trespass, credibility of persistence, and autonomy of owners and managers (Vining & Weimer, 2016). This section elaborates on the property rights that are allocated in the various segments of the natural gas infrastructure. The six dimensions of Vining & Weimer (2016)



are used to assess the allocation of property rights among the various actors active in the infrastructure. The dimensions are defined as follows:

1. The degree of ownership fragmentation refers to “the number of parties who have claims to organizational assets or the financial residuals the assets create.” (Vining & Weimer, 2016, p. 164)
2. “Clarity of allocation refers to the extent to which property rights are comprehensively and unambiguously assigned and specified among owners” (Vining & Weimer, 2016, p. 165).
3. The “costs of alienation refers to the ease with which current property rights can be reallocated.” (Vining & Weimer, 2016, p. 166).
4. Security from trespass refers to how the “effective enforcement of trespass through the institutions of the state can provide high levels of security.” (Vining & Weimer, 2016, p. 166)
5. “Credibility of persistence refers to the strength of the expectation that rights will persist over time.” (Vining & Weimer, 2016, p. 167)
6. The degree of autonomy refers to the extent to which the allocated property rights can be exercised (Vining & Weimer, 2016).

### **Mining companies and the extraction and storage of natural gas**

The production pipeline networks, extraction, and field processing assets are privately owned by the mining companies that exploit a natural gas field. Mining companies can be owned by several public and private shareholders. The natural gas that is produced in the Netherlands is owned by the public-private partnerships that are formed between the mining companies and EBN. Depending on the specific agreement, EBN owns 40 to 50 percent of the shares. This means that EBN has the right to own the benefits from the natural gas that is produced by the mining companies. EBN is not involved in the actual trading and exploitation of natural gas. The rights to sell and use the natural gas are hence fully with the mining companies. The extracted volumes of natural gas are regulated by the ministry. Decision rights on the operations of the natural gas fields are hence public and privately owned. The ministry has the final decision authority to approve the operations in the form of the extraction plans. However, the ministry can only safeguard its goals within the boundaries of these extraction plans and the applicable laws and regulations. The ministry has an economic interest in the extraction of natural gas because of the rights on the revenues of the gas production. This could possible lead to goal tensions in the extraction policy of the ministry.

Decisions on the actual day-to-day operations are with the mining companies. The monitoring of these operations is hence essential. The allocation of property rights regarding the natural gas fields might create principal-agent problems. The permits, the extraction plans, and the laws and regulations are possibly incomplete due to bounded rationality. The SodM needs to enforce the latter regulations and is hence dependent on their completeness. The mining companies own the property rights to exploit a natural gas field through a unique permit. The current property rights are hence hard to reallocate since the permits have a relative long duration and often a possibility to renew it several times. A short-term extraction permit could provide the mining companies with the incentive to generate as much profit on the short-term. The latter could be undesirable for the long-term operations of a natural gas field. Moreover, the investments in the development and operations of a natural gas infrastructure are cost-intensive. Short-term contracts would be undesirable for both economic and safety reasons. The allocation of property rights is hence not resulting in an open market for mining companies.

The credibility of persistence of natural gas seems to be decreasing over the past years. The public and political opinion is shifting towards an energy supply that is based on renewable energy sources. This effect is strengthened by the earthquakes caused by the gas extraction in the province of Groningen.

Hard measures against the reduction of the use of natural gas only seem to hit the small-scale consumers in the current policy plans of the Dutch government.

The storage segment of the natural gas infrastructure follows a similar principal of the allocation of property rights as the production segment. A storage permit is obtained from the ministry and the extraction plans are substituted by storage plans which require different specifications. These storage plans are, in analogy with the extraction plans, approved and enforced by the SodM. The monitoring and enforcement of the rules and regulation of storage activities are also monitored by SodM. The main difference is, however, that EBN is not a silent partner in the storage of natural gas. The right to own the benefits is hence only with the storage operators. This might incentivize to enforce the storage plans differently than the extraction plans. The ministry does not have a direct economic interest in storage and hence dominantly values reliability and social safeguards.

### **Transmission and distribution**

The ownership rights of the Dutch transmission grids are clearly allocated and not fragmented. The Dutch public natural gas transmission grid is 100 percent owned by the Dutch government (i.e. owned by GTS). Private companies own some other transmission pipeline networks next to the grid owned by GTS. The ownership rights of a transmission network include the obligation of performing the role of system operator, as described in the Gas Act. The right to own the benefits from transmission activities are with the transmission system operators. The transportation tariffs are regulated by the ACM. The TSOs have the right to use the transmission grid, the right to own the grid, the right to sell its transportation capacity, and the rights to own the accompanying benefits. TSOs can exercise their activities within the strict rules and regulations about access and tariffs. The degree of property rights infringement is hence rather high. The rights of the privately-owned transmission grids can, in contrast with the grid owned by GTS, be transacted to parties who are not involved in any commercially natural gas related activities. The allocation of property rights to the TSOs is arranged by European and Dutch regulation. A reallocation of these rights would imply the laws and regulation to change. Security from trespass is monitored and enforced by ACM. The autonomy on exercising the property rights are hence with the TSOs under the strict regulations of the ACM.

The distribution segment exhibits a similar allocation of property rights as the transmission segment. The distribution grids are owned by dedicated distribution grid operators, which are publicly owned. Generally, the DSOs are owned by the municipalities they operate in. The clarity of the property rights allocation is hence clear. The right to use the distribution grid is arranged through bilateral agreements with the DSOs. The distribution tariffs and the operations of the DSOs are also regulated by the ACM. Distribution grid operators also have the authority to exercise their property rights within the regulatory boundaries.

The allocation of property right regarding the transmission and distribution grids is forcing the companies into a uniform role. This provides the companies with the incentive to optimize the network development, maintenance, planning, and operation based on this uniform role. No goal tensions from any commercial activities are present.

### **Wholesale market**

The Dutch wholesale market allows for the transaction of the property rights on natural gas. Trade involves the transaction of the right to use, the right to own, the right to sell, and the right to own the benefits of natural gas from one market party to another. The bilateral market is anonymous and closed regarding the specific information on the bilateral agreements. It is hence not exactly clear what the

volumes, prices, and durations are of the bilateral trade. The bilateral market is often used for the purpose of long-term trading. Transactions costs are typically higher due to the bilateral contracts that are needed.

The natural gas that is being traded on the TTF is linked to the volumes (i.e. MWhs) of natural gas that are present in the Dutch transmission grid. Shippers that trade on the TTF transfer the property rights of the volumes of gas that are present in the transmission grid. The natural gas in the Dutch transmission grid can theoretically be traded infinite times in between an entry and exit point. The trade is conducted anonymously, but transparent. GTS registers all the trading that is conducted on the TTF. Many shippers have claims on the various volumes of gas present in the Dutch transmission grid. The TTF is an automated and standardized market platform, which allows transactions to happen on a high frequency involving low transaction costs. The efficient functioning of the TTF is ensured by GTS. ACM enforces the rules and regulations in the wholesale market. The fluctuating price on the TTF, because of the fluctuating demand and supply, is a proper incentive to maximize profits through the natural gas trade. The latter enhances the competitiveness of the natural gas market.

### **Public service obligation of system operators**

From competition law, potential customers of transportation capacities must have access to the capacity services on a non-discriminatory basis. Both the TSOs and the DSOs must ensure that their installed transportation capacity is adequate to ensure that the total demand for transportation capacity can be met. The right to use transmission capacity is auctioned through the Prisma-platform in the forms of annual capacity, quarterly capacity, monthly capacity, daily day ahead capacity, and daily within day capacity (Gasunie Transport Services, 2018j). These forms of capacity rights refer to the various durations of the rights to use a specific amount of transmission capacity for a specific time.

Distribution capacity is sold under fixed prices and cannot be booked. Capacity is hence basically attached to the consumption of natural gas. The right to use distribution capacity are thus obtained through the delivery and supply agreements between the suppliers, the consumers, and the DSO. The ACM enforces the rules and regulations regarding the access and use of transportation capacity. Storage operators are also obliged to provide storage services on a non-discriminatory basis. This includes that a storage operator must provide a storage service if the request is within the operational limits of the storage facility.

### **End use applications**

The large-scale consumers buy gas from the TTF or bilaterally. The small-scale consumers buy the gas from the retail suppliers. End-use equipment and their installment must match strict norms and standards. The ownership rights on the end-use equipment or the rights to use the end-use equipment are basically with the consumers. This allocation of property rights provides the small-scale consumers with the decision rights on their specific installations. The latter involves a significantly high degree of ownership fragmentation in the form of certification, and norms and standards to ensure a safe operation.

#### **3.3.2.6 Spot market rules and operational settlement**

The gas that is traded in the spot market needs to be nominated. A nomination refers to a message from the shippers to GTS in which the shippers inform GTS of all hourly quantities that are traded and need to be transported on the specific network points (Gasunie Transport Services, 2018i). The nomination consists hence of the hourly volumes of natural gas that needs to be transported on specific entry and exit points. Shippers are obliged to nominate all the trade that they conduct (Gasunie Transport Services, 2018i). The nomination obligation applies to every entry and exit point of which a shipper contracted capacity. Nominations are assessed by GTS on their correctness. If a shipper does not have the right on

the transport capacity of a specific network point, the transport will not occur. When shippers trade natural gas, the nominations of both parties are checked. If these nominations do not match, transportation does not occur. Deals can hence not be changed unilaterally by shippers (Gasunie Transport Services, 2018i).

Transport capacity is offered in form of entry and exit capacity. Two ways of transferring capacity are possible between shippers. First, capacity is traded including all its rights and obligations, i.e. referred to as assignment (Gasunie Transport Services, 2018l). Second, only the right to use the capacity is traded, i.e. transfer of use (Gasunie Transport Services, 2018l). Assignment includes the full transfer of the right to own and the right to use the capacity for a given period. Transfer of use only includes the transfer of the right to use for a specific period. The shipper that has the ownership rights on the capacity pays for the capacity services. Shippers are obliged to submit the transfer on the Prisma-platform. Trade in capacity is hence occurring in three ways:

1. Over the counter trade: Shippers trade capacity based on bilateral agreements and submit their bilateral trade agreement of the Prisma-platform (Gasunie Transport Services, 2018l).
2. Call for order trade: Shippers submit a trade proposal to the Prisma-platform to buy or sell capacity. Other shippers make offers to buy or sell the capacity from which the offering shipper can choose (Gasunie Transport Services, 2018l).
3. Call for offer trade: Shippers make a trade proposal to buy or sell capacity which other shippers can accept immediately (Gasunie Transport Services, 2018l).

### **3.3.2.7 Industry standards**

Industry standards are in place in the natural gas sector to contribute to the (inter)national competitiveness and innovation strength, and the mitigation on the impact on health, safety, and the environment. Standardization is conducted on various levels, regionally, nationally, and internationally. The standardization in the natural gas sector basically consists of standards and certification procedures. The standards refer to the standardization of the requirements regarding the products and services, and the assets. The certifications refer to the standardization of the operational methods through certification of personal. The natural gas infrastructure knows a detailed and comprehensive system of industry standards.

### **3.3.3 Coordination: Modes of organization**

The coordination layer of the comprehensive design framework refers to how the interactions between the different actors in the system are organized (Scholten & Künneke, 2016). The transactions that the actors have are organized under given property rights, market structures, and regulations (Scholten & Künneke, 2016). The question is whether the modes of organization are proper mechanisms to achieve a desired outcome. The new institutional economy and the transaction cost theory provide an adequate framework to analyze the various modes of organization within the natural gas infrastructure (Scholten & Künneke, 2016). The focus in this section is hence on the various transactions and the modes of organizations present in the natural gas infrastructure. To investigate the modes of organization in the Dutch natural gas infrastructure, this section elaborates on the contractual arrangements, the degree of horizontal and vertical integration, the transaction costs, and the principal agent and opportunistic behavior safeguards. Contractual arrangements reflect the modes of organization and refer to the legal agreements present in the transactions that occur in the natural gas infrastructure. Horizontal and vertical integration of companies in the natural gas infrastructure define how transaction costs and social hazards are attempted to be minimized. Transaction costs are the costs related to the transactions that actors make. Principal agent and opportunistic behavior safeguards refer to the safeguards that are in place to prevent the costs from opportunism. Figure 24 shows the position of the coordination layer in the four

layers of economic institutions which are referred to as the modes of organization. This section will elaborate on the design of the layer’s specific variables in the natural gas infrastructure.

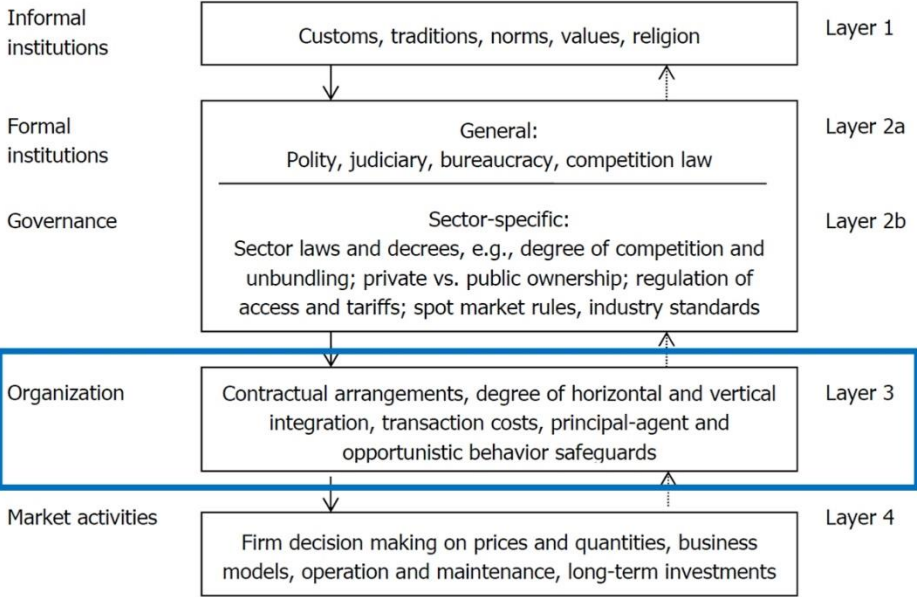


Figure 24: Layer 3 of economic institutions in energy infrastructures, adopted from Scholten & Künneke (2016, p. 12)

**3.3.3.1 Contractual arrangements and the modes of organization**

Contractual arrangements refer to the arrangements between actors that transact. “Transactions are about the transfer of ‘rights to use’ goods or services across technologically separable interfaces.” (Künneke et al., 2010, p. 499) These transactions are coordinated by modes of organization (i.e. contractual arrangements) to ensure the adequate functioning of the infrastructure system. This section distinguishes three types of organizational dimensions for the purpose of identifying the important transactions and their modes of organization. First, the market dimension, that refers to the modes of organization active in the trading of natural gas, storage capacity, and transportation capacity. Second, the technical-control dimension, that Künneke et al. (2010) refer to as the essential modes of organization for the technical functioning of the infrastructure. And third, the organizational dimension, which Künneke et al. (2010) refer to as the transactions that relate to the way that the economic and social viability of the infrastructure system is organized.

The market dimension generally consists of the transactions of volumes of natural gas, the transactions of transport capacity, and the transactions of storage capacity. Hazards potentially exist because of the high asset specificity in production and transportation assets. Safety, economic, social and environmental hazards potentially exist because of the nature of the natural gas provision. The publicly managed market, under the supervision of ACM, should prevent these hazards. The bilateral transactions of natural gas between the shippers are basically free to make. The bilateral trade is organized by GTS in a way that the including capacity of the trade needs to be booked and nominated by the shippers. Transportation capacity is transacted between the system operators and the shippers and among the shippers. New transmission capacity is auctioned by GTS. Distribution capacity is transacted through bilateral contracts between DSOs, retail suppliers, and consumers. The prices are fixed and regulated by ACM. Storage capacity is traded between the storage operators and the interested shippers through bilateral contracts.

The technical-control dimension consists of the modes of organization that are in place to ensure the reliable and robust functioning of the infrastructure. The interconnection between the production, transmission, storage, distribution, and consumption systems is assured through a strict framework of gas requirements, stated in the Dutch Gas Quality Regulations (i.e. no. WJZ/13196684). This framework states the specific gas qualities and pressures to be used in the specific transportation systems. Production, storage, and consumption systems need to adopt their gas qualities and pressure levels to the specific grid characteristics. The natural gas infrastructure is organized through the collaborative supervision of the various system operators. Bilateral agreements ensure the right requirements of the transfer of gas between the systems. A general framework of system norms and standards is organizing the interoperability of the various components in the gas grids.

The natural gas infrastructure requires modes of organization that ensure the economic and social viability of the system. Production, transportation, and storage capacity adequacy needs to be organized and safeguards need to exist for opportunism and potential safety hazards. The production and storage capacity are organized under long-term contracts between the Ministry and the mining companies. This is to reduce the uncertainty of the investment in assets with a large degree of asset specificity. Moreover, the Ministry controls the production and storage capacity adequacy through the extraction and storage plans. The TSOs and DSOs have a public service obligation to allow third party access to their transportation capacity. The latter is monitored and enforced by ACM. The opportunism and safety safeguards are publicly regulated through the laws and regulations and enforced by SodM, Human Environment and Transport Inspectorate (ILT), and ACM.

**3.3.3.2 Degree of horizontal and vertical integration**

The degree of horizontal and vertical integration will be discussed following the natural gas supply chain activities as illustrated in Figure 25. The exploration, production, and storage activities are conducted by the Mining companies. Transmission activities are only conducted by TSOs and distribution activities only by DSOs. Energy companies can be active in the trading and retail of natural gas. The metering is the responsibility of recognized metering companies and the system operators. Mining companies are generally active in the wholesale market. Mining companies can own and operate several natural gas fields and storage facilities. The transmission activities are fully unbundled from other activities that are not related to the transmission of natural gas. The DSOs are next to the distribution of natural gas also active in the distribution of electricity. Energy companies can also be both active in the supply of electricity and natural gas.

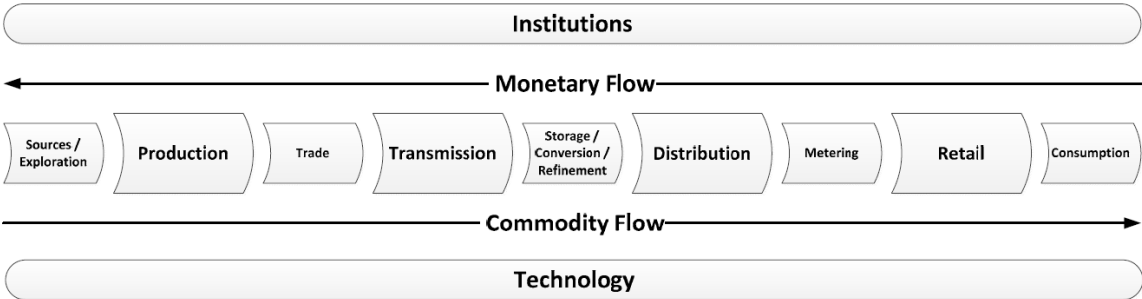


Figure 25: energy infrastructure supply chain, adopted from Scholten & Künneke (2016, p. 4)

**3.3.3.3 Transaction costs**

Non-specific transactions in the Dutch natural gas infrastructure that recurrently occur are the transactions in the volumes of natural gas and transportation capacity in the wholesale market. These transactions are subject to market governance. To reduce the costs of uncertainty, the goods and services are standardized. Long-term bilateral contracts between suppliers and customers on the volumes of natural gas are not standardized and subject to bilateral-governance. The capacity contracts with system operators are all standardized contracts that are regulated. The latter is to reduce the transactions cost regarding uncertainty. Transactions that are recurrent and nonspecific are the transactions in standard production, transportation, and consumption equipment with a significant low degree of asset specificity. The chance of opportunism within the latter category of transactions is mitigated through the comprehensive legal framework of conditions and through the standardization of the equipment. The transaction costs are further reduced due to the experience, expertise, and existing relations of the buyers and sellers.

An example of occasional transactions with under high uncertainty are investments in natural gas production sites, transportation infrastructure, and large-scale end use applications. The principal of these contracts are that parties have “strong incentives to see the contract through completion” (Williamson, 1979, p. 249). The latter refers to the high asset specificity in terms of the physical assets, the human assets, the site specificity, and dedicated assets. The recurrence of the transactions would imply significant difficulties. The larger the uncertainty and asset specificity, the larger the interest of the principals gets to sustain the contractual arrangements (Williamson, 1979). The costs of regulating such transactions by transaction-specific governance structures are often higher than the benefits (Williamson, 1979). Instead, the transaction costs ought to be minimized by the interference of independent public arbitration bodies to interfere with the contracting and to settle disputes (Williamson, 1979). The SodM and the ACM are examples of the public bodies that see to the latter.

An example of bilateral governance are the long-term supply contracts. Examples are the exploitation and storage agreements between the mining companies and the ministry. Bilateral governance generally involves high contracting costs. The parties involved in the bilateral agreements want a certain degree of flexibility within the contracts to adopt to the changing market. Only the activities that can cause potential hazards need to be hedged to restrict the opportunities for opportunism. The transaction costs can hence be mitigated through experience, expertise, and existing relations of the buyers and sellers. Buyers will likely choose the same suppliers, since setting up other bilateral agreements will imply higher transactions costs (Williamson, 1979). Due to the large market share of the trade via the spot market, the duration of bilateral trade decreases in the Netherlands (L. J. de Vries et al., 2010). Prices in the spot market are thus increasingly attractive compared to the bilateral prices.

#### **3.3.3.4 Principal-agent and opportunistic behavior safeguards**

Asset specificity in the Dutch natural gas infrastructure is high. Dedicated assets are in place, since the assets of the natural gas infrastructure are designed for the purpose of the natural gas provision. Site specificity exists due to the specific locations of the natural gas fields. Human asset specificity is also present and refers to the specialized skills present in companies active in the natural gas provision. To prevent hazards from happening, a regulatory framework is in place that regulates the provision of gas and the functioning of the market. The public involvement in the production of natural gas is a safeguard to ensure safety, environmental, and economic goals. The ACM and SodM control whether the public-private partnerships are safeguarding hazardous situations in the production of natural gas. The public-private partnership is also a safeguard to control the access to the natural gas fields publicly. Access to the TTF is organized through the public monopoly as a safeguard for discrimination. Transmission activities are integrated in the same public monopoly. This is to safeguard the safe, reliable, and

economic viable functioning of the transmission grid. Metering activities, conducted by licensed parties<sup>5</sup>, are a safeguard to prevent inaccuracies or opportunism. The assets utilized within the natural gas infrastructure are all subject to a strict regulatory framework of conditions and standards to safeguard hazardous situations from unsuitable assets. The same applies to the gas utilized in the infrastructure.

### 3.4 Complementarity in the design of thee natural gas infrastructure

The complementarity between the technical and market design of the natural gas infrastructure can be assessed along the categorization of the production, transmission, distribution, and storage, activities regarding both the technical operational dimension and market dimension. When the categories do not match between the layers it could be argued that disalignment exists between the dimensions of energy infrastructure design. Table 7 includes the assignment of the categories as defined in the operationalization of the comprehensive design issues. No clear disalignment issues between the institutions and technology of the system can be identified because of the categorization in Table 7. It can be argued that alignment exists between the technology and institutions of the natural gas infrastructure, since the categories are filled in consistent fashion, see Table 7. Small

	<b>Technical operational activities</b>		
<b>Layer of abstraction</b>	<b>Access</b> (allowed to participate)	<b>Responsibilities</b> (control and intervention tasks)	<b>Coordination</b> (centralized vs decentralized)
<b>Perspective</b>			
Production	Access through property rights infringement	Delegated responsibility	Decision rights infringement
Transmission	Closed access	Public responsibility	Public entity coordination
Distribution	Closed access	Public responsibility	Public entity coordination
Storage	Conditional access	Delegated responsibility	Decision rights infringement
	<b>Market activities</b>		
<b>Layer of abstraction</b>	<b>Access</b> (state vs market)	<b>Responsibilities</b> (Ownership & decision rights)	<b>Coordination</b> (Vertically integrated vs market)
<b>Perspective</b>			
Production	Delegated access	Public-private responsibility	Public-private coordination
Transmission	Closed access	Public responsibility	Public coordination
Distribution	Closed access	Public responsibility	Public coordination
Storage	Conditional access	Public-private responsibility	Public-private coordination

Table 7: The assignment of the comprehensive design issue categories to the layers in the natural gas infrastructure

<sup>5</sup> Metering is strictly regulated by the system operators because of the importance of the correctness of the metering activities. Actors that want to become metering responsible need to be acknowledged by Tennet. Under strictly controlled circumstances by the system operators it is possible for actors to perform the metering responsibility of their own connections. The ownership of the metering installations is with the system operators and the metering responsible parties. The tariffs of the small-scale connections are fixed by the ACM and the larger-scale connection tariffs are determined by the metering companies. Metering is the responsibility of all the metering responsible parties. It is controlled by the system operators and supervised by the ACM. Actors with large-scale connections can freely choose their metering responsible company on the basis of their preference.



## 4. Feasible hydrogen infrastructure configurations

This chapter addresses the third sub research question, *what hydrogen infrastructure configurations are feasible to replace natural gas in the Dutch natural gas infrastructure for the heat provision of the residential and service sector?*

The focus of this question is on hydrogen infrastructure configurations that make use of the existing natural gas transportation infrastructure in the Netherlands. To answer the question, options to replace natural gas for hydrogen in the natural gas grid need to be identified. These options are investigated in terms of their feasibility to be integrated in the Dutch natural gas infrastructure.

Paragraph 4.1 starts with an introduction to the utilization of hydrogen in the natural gas infrastructure and the accompanying hydrogen production, storage, transportation and consumption technologies. Paragraph 4.2 elaborates on the selection of the two hydrogen infrastructure configurations that will be investigated.

### 4.1 Hydrogen as a fuel for heating in the Dutch natural gas infrastructure

Hydrogen gas has the potential to replace natural gas as an energy carrier in the current natural gas infrastructure (Dodds & Demoullin, 2013; Dodds & McDowall, 2013; Messaoudani, Rigas, Binti Hamid, & Che Hassan, 2016; van Wijk & Hellinga, 2018). Hydrogen does not exist in an elemental form within nature and therewith needs to be produced from compounds that contain it (Ekins, 2010). The basic properties of the hydrogen molecule is that it is the lightest of all molecules with a density of seven percent of the density of air (Rand & Dell, 2008). Hydrogen gas is colorless, odorless, tasteless, and non-toxic (Rand & Dell, 2008). Liquid hydrogen has the highest gravimetric energy density of all fuels, but its volumetric energy density is rather poor (Rand & Dell, 2008). The main advantage of the utilization of hydrogen over natural gas basically rests on the potential to mitigate the pollutive effect of the natural gas combustion and to solve security of supply issues of natural gas as it is depletable. If hydrogen is replacing natural gas, the differences in the physical and chemical characteristics of hydrogen gas and natural gas need to be addressed (Messaoudani et al., 2016). Table 8 provides the main properties of hydrogen and methane (i.e. the main compound of natural gas). The injection of hydrogen into the natural gas infrastructure will, due to the differences in chemical and physical properties, result in different combustion and calorific values than with natural gas. Moreover, hydrogen gas will cause the pressure and temperature to drop and might also effect the material properties of the pipeline networks and their assets (Messaoudani et al., 2016).

Properties	Hydrogen (H <sub>2</sub> )	Methane (CH <sub>4</sub> )	Unit
Molar mass	2.02	16.04	g/mole
Critical temperature	33.2	190.65	K
Critical pressure	13.15	45.4	Bar
Vapor density at normal boiling point	1.34	1.82	Kg/m <sup>3</sup>
Vapor density (at T = 293.15 K and P = 1 bar)	0.0838	0.651	Kg/m <sup>3</sup>
Specific heat capacity (at T = 293.15 K and P = constant)	14.4	2.21	kJ/kg/K
Specific heat ratio (C <sub>p</sub> /C <sub>v</sub> )	1.4	1.31	–
Lower calorific value by mass (lower heating value, weight basis)	120	48	MJ/kg
Lower calorific value by volume at 1 atm	11	35	MJ/m <sup>3</sup>
Higher calorific value by mass	142	53	MJ/kg
Higher calorific value by volume at 1 Atm	13	39	MJ/m <sup>3</sup>
Maximum flame temperature	1800	1495	K
Explosive (deniability) limits	18.2–58.9	5.7–14	Vol % in air
Limiting oxygen for combustion	5	12	Vol %
Flammability limits	4.1–74	5.3–15	Vol % in air
Auto-ignition temperature	560	600	°C
Laminar burning velocity	3.1	0.4	m/s
Dilute gas viscosity at T = 299 K	9 × 10 <sup>-6</sup>	11 × 10 <sup>-6</sup>	Pa × s
Molecular diffusivity in air	6.1 × 10 <sup>-5</sup>	1.6 × 10 <sup>-5</sup>	m <sup>2</sup> /s
Solubility in water	0.0016	0.025	kg/m <sup>3</sup>

Table 8: Main properties of hydrogen and natural gas

The chance that hydrogen leakages occur from pipelines is approximately 1.3 to 2.8 times larger than the change of methane leakages (Messaoudani et al., 2016). This is because hydrogen is lighter than natural gas. The hydrogen leaks can have more severe consequences than the leaks of natural gas since hydrogen ignites much easier than natural gas (Messaoudani et al., 2016). The ignition of hydrogen may automatically occur because of the turbulent blending between hydrogen and ambient air (Messaoudani et al., 2016). Furthermore, ignition sources as sparks from electrical equipment, rapid closing valve stations, or electrostatic discharges could cause hydrogen to ignite (Messaoudani et al., 2016). Hydrogen has larger flammability and explosive limits than natural gas. The risks of uncontrolled releases of hydrogen are hence much larger than with natural gas. Hydrogen fires are harder to detect since they burn with a pale blue flame that neither produces light in daylight nor smoke (Messaoudani et al., 2016). The utilization of hydrogen in the natural gas infrastructure can affect the functioning of the gas detection and metering installations that are currently in place. Hydrogen may not be detectable by the gas detection equipment designed for the detection of natural gas (Messaoudani et al., 2016). Metering installations may hence not work properly. When hydrogen is utilized in the natural gas grid, the possibility for hydrogen leakages may be enlarged because hydrogen may damage its materials and installations. Hydrogen has the property to induce damage by its interaction with various materials such as steel, iron, and carbon (Djukic, Bakic, Zeravcic, Sedmak, & Rajjic, 2016). Hydrogen damages can be classified in hydrogen-induced cracking, hydrogen-stress cracking, hydrogen embrittlement, and high temperature hydrogen attack (Djukic et al., 2016). The possible effects of hydrogen on the materials of the Dutch natural gas infrastructure need to be investigated.

The chemical and physical properties of hydrogen require the natural gas infrastructure to be modified for the utilization of hydrogen. Adequate amounts of hydrogen need to be produced, stored, transported, and distributed safely to the end-user. The technologies and assets used in the natural gas infrastructure need to be compatible with the use of hydrogen. Large-scale hydrogen production and storage methods need to be developed. Stationary end-use applications in the residential and service sector need to be compatible with hydrogen and need to satisfy the heat demand.

### **4.1.1 Hydrogen production**

The production of hydrogen can be based on a variety of production methods using different primary energy sources. Basically, hydrogen can be produced from fossil fuels, biomass, organic waste, and electricity. There exist different production methods to produce the hydrogen from the latter energy sources, and within the production methods there are also variations possible. This section will elaborate on the basic principles of steam reforming, gasification and pyrolysis, and electrolysis. The section concludes with an assessment of the techno-economic characteristics of the production methods discussed.

#### **4.1.1.1 Reforming based hydrogen production**

Steam reforming (SR) is currently widely used in both the chemical as the refinement industries and can currently be considered as the most common way of producing hydrogen (Bolat & Thiel, 2014b; Ekins, 2010). The production method of SR makes use of hydrocarbon gasses (i.e. methane/natural gas) as an energy source and can be considered as a relatively low carbon emitting hydrogen production technology (Bolat & Thiel, 2014b). Other advantages are its co-production flexibility through the co-utilization of steam, and the hydrogen production scale flexibility (Bolat & Thiel, 2014b). The latter makes SR feasible to utilize in both the centralized (i.e. large scale) and decentralized (i.e. smaller scale) production of hydrogen (Bolat & Thiel, 2014b). The main chemical reactions of SMR consist of a highly endothermic and reversible reforming reaction and a slightly exothermic water gas shifting reaction (Bolat & Thiel, 2014b). The endothermic reaction of desulfurized gas with high-temperature steam results in a mixture of hydrogen and carbon monoxide (i.e. syngas). The exothermic water gas shift reaction is used to obtain a mixture of pure hydrogen and CO<sub>2</sub> from the Syngas (Ekins, 2010). The pure hydrogen is obtained from the latter mixture using pressure swing adsorption (PSA), which separates the hydrogen from the other gas. The remaining gas is often recycled or used for the reforming process (Ekins, 2010). The production process causes CO<sub>2</sub> emission and makes it therewith necessary to capture the CO<sub>2</sub> to make the process of SR carbon neutral. The energy that is necessary for the high-temperature steam leaves a carbon footprint depending of the source of energy that is used. Natural gas is often used in the endothermic reaction. Other hydrocarbons can also be applied but are not widely deployed yet.

#### **4.1.1.2 Gasification and pyrolysis**

Coal gasification is widely used to produce hydrogen in the chemical and refinement industries, and increasingly in the generation of electricity (Bolat & Thiel, 2014b; Ekins, 2010). Other fossil fuels can also serve as the input of the process. The specific hydrogen yields of the process are dependent on the characteristics of the fossil fuels that are used (Bolat & Thiel, 2014b). The hydrogen production process can produce syngas (CO and H<sub>2</sub>), producer gas (a mixture of syngas), methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>), and Nitrogen (N<sub>2</sub>) (Bolat & Thiel, 2014b). The production process basically consists of three subsequent stages, pyrolysis, combustion, and gasification (Bolat & Thiel, 2014b). First, pulverized coal is heated to temperatures higher than 700 °C in the absence of oxygen (Bolat & Thiel, 2014b). This reaction of fuel with heat has producer gas (H<sub>2</sub> and CH<sub>4</sub>), tars, and char as products (Bolat & Thiel, 2014b). Second, in the combustion stage, the products from the pyrolysis stage react with oxygen. The products from the combustion stage are carbon dioxide and syngas (CO). In the gasification stage, the products from the combustion stage are exposed to high-temperature and high-pressure air or pure oxygen to produce usable syngas (CO and H<sub>2</sub>) (Ekins, 2010). The benefits of using pure oxygen over air are in the purity of the syngas that is produced. With pure oxygen the subsequent gas cleaning and separation are more convenient (Ekins, 2010). The syngas can be used after the cleaning from hydrogen sulfide and other impurities (Ekins, 2010). In analogy with SMR, the water shift reactor makes CO reacting with water to produce CO<sub>2</sub> and hydrogen. The hydrogen can be subtracted by PSA or by an amine-based absorbent (Ekins, 2010). The CO<sub>2</sub> from the production process, including the energy

needed for the high-temperature and high pressure, should be captured to make the production processes carbon neutral. This production process emits about 20 percent lower CO<sub>2</sub> emissions than the conventional combustion power plants and gasification and pyrolysis are promising technologies to achieve a CO<sub>2</sub> free hydrogen production future (Bolat & Thiel, 2014b).

The gasification and pyrolysis with biomass as a feedstock, provides a way to produce hydrogen from biomass (Ekins, 2010). These production processes can use various kinds of feedstock with different requirements for pre-treatment and different hydrogen yields (Bolat & Thiel, 2014b). Biomass pyrolysis produces pyrolysis oil (i.e. bio-oil) in reaction with the condensed vapors of the gas mixture caused by the rapidly heating of biomass in the absence of oxygen. Bio-oil improves the storability and transportability of the carbon in the biomass and contains a higher energy density (Ekins, 2010). The non-condensable gases and char formed in the pyrolysis step can be partly combusted to provide a part of the energy needed in the process. With biomass gasification and pyrolysis, the biomass follows similar production steps as with the gasification of fossil fuels. The reforming stage of the syngas is very similar to that of SMR (Ekins, 2010). The energy inputs of the biomass production, and the biomass gasification and pyrolysis process, excluding the carbon that is captured from the atmosphere by the biomass feedstock, represent the carbon footprint of biomass gasification and pyrolysis. Apart from the energy inputs of the biomass production, biomass gasification and pyrolysis are conceived to be carbon neutral (Ekins, 2010).

#### **4.1.1.3 Water electrolysis-based hydrogen production**

Water electrolysis is mostly characterized based on the solution that is used as the electrolyte and based on the source that is used for the electricity generation. Electrolytes that are often used are Alkaline electrolyzers or proton exchange electrolyzers (Bolat & Thiel, 2014b). Primary energy sources for the generation of electricity mostly include high-temperature steam, solar, and wind (Bolat & Thiel, 2014b). The characteristics of the electrolytes and the primary energy sources primarily determine the costs of the electrolysis-based hydrogen productions. The latter two have direct effects on the efficiency and the capital costs of the production system, and the electricity price (Bolat & Thiel, 2014b). In water electrolysis, water is split into hydrogen and oxygen. Basically, water reacts with electricity and heat to form hydrogen and oxygen. This reaction can be triggered using different combinations of cathode-anode reactions and electrolytes (Bolat & Thiel, 2014b). The three most common types of combinations are alkaline electrolyzers (AE), proton exchange membrane electrolyzers (PEME), and solid oxide electrolyzers (SOEC). AE uses potassium hydroxide as an electrolyte and uses nickel electrodes. (Bolat & Thiel, 2014b). Their operating temperature is 40 to 90 °C. AE has a 80 percent conversion efficiency and produce 99 percent pure hydrogen (Bolat & Thiel, 2014b). Drawbacks from AEs are their low partial load range, limited current density, low operating pressure, and high ohmic losses (Bolat & Thiel, 2014b). PEME basically reverses the process of the PEM fuel cells. PEME uses Nafion as electrolyte, which is a synthetic polymer with ionic properties (Bolat & Thiel, 2014b). PEME uses noble metals as electrodes and their operating temperature is 20 to 100 °C (Bolat & Thiel, 2014b). In contrast with AE, PEME can be used in the distributed generation of hydrogen (Bolat & Thiel, 2014b). Main advantages of PEME over AE are their ability to operate at higher current densities, their higher chemical and mechanical stability, their lower maintenance requirements, their better integration with high-pressure electrolysis, and their dynamic operation and high hydrogen purity levels (Bolat & Thiel, 2014b). Drawbacks from PEMEs are low durability, and high capital and operational costs (Bolat & Thiel, 2014b). The application of SOEC is still in a laboratory stage. Despite that, SOEC is a highly promising option for achieving high production efficiencies (Bolat & Thiel, 2014b). Main advantages are their thermo-neutrality and the use of inexpensive materials (Bolat & Thiel, 2014b). They have an operating

temperature of 700 to 1000 °C. The CO<sub>2</sub> footprint of electrolysis is strongly determined by the energy source used to produce the needed electricity.

#### 4.1.1.4 Comparison between hydrogen production technologies

Hydrogen production technologies are generally categorized based on their capacity. Production technologies with large capacities refer to the centralized production of hydrogen. Production technologies that have relatively small capacities based on the on-site production of hydrogen refer to the decentral production of hydrogen. The categorization of hydrogen production technologies used in the thesis project is as follows, centralized production options of hydrogen are:

1. steam methane reformation with CCS,
2. steam methane reformation without CCS,
3. coal gasification and pyrolysis with CCS,
4. coal gasification and pyrolysis without CCS,
5. biomass gasification and pyrolysis with CCS,
6. biomass gasification and pyrolysis without CCS, and
7. water electrolysis.

The decentralized production options are:

1. medium-scale steam methane reformation with CCS,
2. medium-scale steam methane reformation without CCS,
3. small-scale steam reformation, and
4. small-scale water electrolysis.

The hydrogen production technologies can be compared along several performance parameters. Important performance parameters for the feasibility of the hydrogen production technologies are the availability factor, hydrogen costs (i.e. investment, operational, and maintenance), capacity, energy efficiency, and lifespan. Different studies reviewed by Bolat & Thiel (2014) consider the various performance indicators of the hydrogen production technologies. Table 9 shows an overview of the hydrogen production technologies and their accompanying performance ranges as presented in Bolat & Thiel (2014). A distinction is made in the following hydrogen production technologies: coal gasification, biomass gasification, centralized steam reformation from biomass, centralized steam reformation from methane, decentralized steam reformation from methane, centralized alkaline electrolysis, and decentralized alkaline electrolysis. As indicated above, the performances are based on a variety of studies including various characteristics in their calculations. The hydrogen production technologies based on gasification and steam reformation both include the performance parameters of the inclusion of options with carbon capture and storage (CCS).

Parameters	Availability factor		Hydrogen costs		Capacity		Energy efficiency		Lifespan	
H <sub>2</sub> Production Technologies	[%]		[MM€/PJ]		[MW]		[KW/KW H <sub>2</sub> ]		Years	
	min	max	min	max	min	max	min	max	min	max
Coal gasification	80	90	5.2	10.26	450	1667.7	1.69	1.96	20	25
Biomass gasification	71	90	25.28	46.13	0.71	204.39	2.04	3	20	20

Parameters	Availability factor		Hydrogen costs		Capacity		Energy efficiency		Lifespan	
H2 Production Technologies	[%]		[MM€/PJ]		[MW]		[KW/KW H <sub>2</sub> ]		Years	
	min	max	min	max	min	max	min	max	min	max
Centralized steam reformation from biomass/ bio oil	90	90	10.87	14.62	222	235	1.36	1.88	20	20
Centralized steam reformation from methane	90	90	17.55	25.26	33	1530	1.38	1.65	20	40
Decentralized steam reformation from methane	86	90	14.58	34.62	14.6	70.72	0.9	1.81	20	25
Centralized alkaline electrolysis	90	90	37.74	47.44	33	125	1.3	1.63	20	40
Decentralized alkaline electrolysis	90	90	38.52	55.58	0.6	3	1.27	1.62	20	20

Table 9: hydrogen production technologies and their performance indicators, obtained from Bolat & Thiel (2014)

The costs of coal gasification-based hydrogen production are largely determined by the high capital costs of the production system (Bolat & Thiel, 2014b). The costs of coal are currently rather low. Increasing costs of coal or CO<sub>2</sub> emissions could increase the hydrogen production costs. Coal gasification without CCS generates in between 571 and 721 kilograms of CO<sub>2</sub> per MWh of hydrogen produced (Muradov, 2017). With CCS included in coal gasification, the amount of CO<sub>2</sub> emitted per MWh of hydrogen lays around 57 kilograms (Bolat & Thiel, 2014b; Man, Yang, Xiang, Li, & Qian, 2014). The costs of biomass gasification-based hydrogen production are also mainly determined by the capital cost of the production system (Bolat & Thiel, 2014b). Biomass gasification includes higher hydrogen production costs than coal gasification due to the higher price of the biomass compared to coal. Biomass gasification includes approximately 264 to 345 kilograms CO<sub>2</sub> emissions per MWh of hydrogen produced (Arvidsson, Morandin, & Harvey, 2015; Bolat & Thiel, 2014b). This can be further reduced if CCS is applied. With reforming based hydrogen production of both biomass and methane, the capital costs are relatively lower compared to the other production technologies (Bolat & Thiel, 2014b). The fuel costs are related to the price of natural gas and biomass. Very small-scale applications of SR make it difficult to apply CCS. Steam methane reformation emits approximately 261 to 312 kilograms of CO<sub>2</sub> per MWh of hydrogen produced (Muradov, 2017). Alkaline water electrolysis has the highest fuel cost and the lowest investment cost compared to the other hydrogen production technologies (Bolat & Thiel, 2014b). Water electrolysis is currently largely based on the use of conventional electricity. The fossil fuels are causing water electrolysis to have a relatively poor environmental performance. Water electrolysis emits approximately 721 to 841 kilograms of CO<sub>2</sub> per MWh of hydrogen produced (Muradov, 2017).

### 4.1.2 Hydrogen storage

Hydrogen can be stored, in analogy with natural gas, as a compressed gas, a liquid, in a chemical compound, or physically held by structures such as hydrides. The different forms of hydrogen find different storage applications. The key determinants of the storage costs of the different forms are the storage time, the storage capacity, and the energy requirements (Ekins, 2010). Potential storage technologies are compressed hydrogen gas storage, liquid hydrogen storage, hydrogen storage as a chemical and metal hydride, and underground hydrogen gas storage. Compressed gas storage will be necessary if hydrogen will be utilized in the natural gas infrastructure.

The compressed gas storage is already widely used in the refining and chemical industries (Ekins, 2010). Compressed gas storage of hydrogen requires less energy than the liquification and is easier scaled down (Ekins, 2010). As a downside, it suffers from a low volumetric energy density and relative costly storage tanks (Ekins, 2010). The compressed hydrogen gas storage is still under debate, because of the safety issues that it would or would not include (Ekins, 2010). Liquified hydrogen storage is merely applied in the refinement industries. Due to the low boiling point of hydrogen, the equipment for liquified storage and handling is more expensive than the equipment used for LNG (Ekins, 2010). Another problem with the liquified hydrogen is its boil-off (evaporation) properties. The boil-off of liquified hydrogen will always occur and is dependent on the characteristics of the storage vessel. A typical boil-off rate lays around the 0.1% per day, the boiled-off hydrogen gas can either be used immediately, stored, re-liquified, or allowed to build up pressure within the storage vessel's limits (Ekins, 2010). Hydrogen can also be stored as a hydrate (i.e. physically), either as a chemical hydrate or as a metal hydrate. Hydrates are stored as a slurry with a mineral oil which makes the conventional storage tanks applicable for their storage (Ekins, 2010). Chemical hydrates are for example hydrates of hydrogen and calcium, magnesium, or lithium. These elements have higher volumetric and gravimetric energy densities than liquified hydrogen and the hydrogen can be liberated when they are exposed to water (Ekins, 2010). The hydrolysis reaction of the chemical hydrates is highly exothermic (i.e. it generates heat). The regeneration process of the hydrate is highly endothermic and therewith costly and inefficient (Ekins, 2010). With a metal hydrate, in contrast with a chemical hydrate, the adsorption of hydrogen (i.e. production of the hydrate) is exothermic and the releasing of hydrogen is endothermic. The main advantage of hydrates is that they are inherently safe without danger for leaks or runaway reactions (Ekins, 2010). The main drawback of hydrates is that they are very heavy, and therewith not feasible to economically transport. Another problem of hydrates is that they have a very slow rate of hydrogen release (Ekins, 2010).

Underground hydrogen storage refers to the storage of pure hydrogen gas in underground storage facilities. The principle is similar to how oil and natural gas are widely stored in depleted gas reservoirs, salt caverns, and aquifers (Ekins, 2010). Salt caverns are proven to be feasible, both economically and geologically, for the storage of hydrogen and are already used in the United States, Britain, and Germany (Lord, Kobos, & Borns, 2014; Panfilov, 2016). The properties that salt caverns are almost completely hermetic, have a high degree of cleanliness, and include a low risk of probable gas contaminations by impurities (Panfilov, 2016). These properties make salt caverns geologically feasible for the storage of hydrogen (Panfilov, 2016). Depleted gas reservoirs and aquifers can store much larger volumes of hydrogen gas than salt caverns. The chemical and physical behaviors of underground hydrogen storage are significantly different from that of natural gas. The applicability of the underground storage facilities to store hydrogen hence needs to be investigated per specific facility (Panfilov, 2016). The costs of storing hydrogen per kilogram are calculated by Lord et al. (2014) for various storage possibilities in

the United States. The costs of aquifers, salt caverns, and depleted reservoirs are respectively 1.29, 1.61, and 1.23 \$/kg (Lord et al., 2014).

### **4.1.3 Hydrogen transportation and distribution**

Transporting hydrogen through pipelines is the cheapest and safest way to transport hydrogen over long distances with minimal energy losses (Messaoudani et al., 2016). An extensive hydrogen pipeline network will allow for the transportation and storage of a sizable quantity of gas that can function as a buffer (Ekins, 2010). Currently, hydrogen gas is delivered by pipelines in several areas of Europe, Canada, and the United States (Ekins, 2010). The hydrogen pipelines usually do not make up an extensive network, they rather facilitate the direct transport from producers to consumers. The longest hydrogen pipeline in the European Union connects France with Belgium by a pipeline of 400 kilometers. The injection of pure hydrogen in the Dutch natural gas grid would introduce a cost-effective solution for the transportation of hydrogen. Despite the potential of injecting hydrogen in the natural gas grid, there are also potential hazards that need to be investigated (Messaoudani et al., 2016). The transportation of hydrogen must ensure the same safety levels as the transportation of natural gas before it can be broadly utilized in the natural gas infrastructure. Next to hydrogen gas, liquified hydrogen can be transported by road tube trucks, road tankers, and ship tankers. Road tankers are the most commonly used within the chemical and refining industries, and ship tankers do not yet exist for hydrogen (Ekins, 2010). It is reported that Canada has some designs for hydrogen ship tankers with a capacity of 14 million kilograms of liquified hydrogen (Ekins, 2010).

### **4.1.4 Hydrogen stationary end-use applications in the residential and service sector**

Hydrogen end-use applications for the residential and service sector can be based on the combustion of hydrogen or on the use of fuel cells. Fuel cells in combination with an electric heat pump can achieve higher efficiency levels than the conventional combustion of hydrogen gas (Hermkens et al., 2018). The natural gas end-use applications of the Dutch residential and service sector are currently compatible with the combustion of natural gas. The replacement of natural gas by hydrogen in the installed natural gas condensing boilers can hamper the functioning of the boilers. The combustion of hydrogen includes a lower calorific value and an increased laminar burning velocity (H. de Vries, Mokhov, & Levinsky, 2017). The latter refers to the property of hydrogen that is related to flame stability issues, such as flashback (H. de Vries et al., 2017). The technologies in the current natural gas condensing boilers are hence not compatible with the use of hydrogen (Hermkens et al., 2018). Hydrogen condensing boilers need to be developed that allow for a safe and efficient combustion of hydrogen. The utilization of the fuel cells would require the replacement of the natural gas condensing boilers. Moreover, fuel cells and heat pumps need to be installed. Fuel cells can have, depending on the type, problems with the existence of impurities in the hydrogen. Component such as CO<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub>, and the current liquid used for odorization (i.e. THT) can hamper the functioning of fuel cells (Hermkens et al., 2018).

### **4.1.5 Hydrogen policy**

Currently, there is no specific hydrogen act as we know the gas, electricity, and heat acts. The use of hydrogen is regulated by general laws and regulations on the transportation, storage, and use of highly compressed gasses and dangerous commodities. Norms and regulations apply to the different production, storage and transportation facilities and the accompanying activities. These formal institutions are basically in place to guarantee the safety of the public. Hydrogen is currently traded as a private good under the market structure of the EU and the specific countries.



## 4.2 Hydrogen infrastructure configurations

This section elaborates on the selection of the hydrogen infrastructure configurations that will be investigated in the thesis project. Hydrogen infrastructure configurations refer to the different options of combining hydrogen production methods with means to transport hydrogen and deliver it to the end-use applications. Basically, a hydrogen supply chain would include the following steps: the production of hydrogen by the transformation of natural resources to hydrogen, the transmission and distribution of hydrogen, and the conversion of hydrogen to the quality that is needed in the end-use applications. Hydrogen production technologies, as described above, can be categorized regarding their capacities. Hence two broad categories are the large-scale (i.e. centralized) and small-scale (i.e. decentralized) production of hydrogen. The former category refers to the need for hydrogen to be transported over longer distances to the areas of demand. The latter category refers to the on-site production which requires the hydrogen to be transported over relatively small distances.

The produced hydrogen needs to be conditioned and delivered from the production site to the areas of demand. Processes that include the transportation of hydrogen are underground storage, liquification, compression, and storage in tubes (Bolat & Thiel, 2014a). The actual transportation of hydrogen can, as discussed above, be conducted in several ways. This thesis project focusses on the replacement of natural gas by hydrogen gas in the Dutch natural gas grid. Pipeline transportation is hence the only means of transportation that will be investigated. The focus is therewith on the identification of hydrogen infrastructure configurations that are based on the delivery of gaseous hydrogen by a pipeline system. The potential and existing end-use applications of hydrogen can be found in the transportation sector, and in the stationary applications of the large- and small-scale consumers. The focus of the thesis project is on the replacement of natural gas in the heat provision to the residential and service sector. The utilization of hydrogen in the transportation sector and in the stationary applications of the large-scale consumers are hence out of the scope of this thesis project. The stationary end-use applications of the residential and service sector are included.

Bolat & Thiel (2014a) identify a broad variety of hydrogen pathways based on the various possible combinations of hydrogen production technologies, means of transportation, and end-use applications. Within the scope of the thesis project, the admixture of natural gas with hydrogen is excluded. Moreover, the thesis only focusses on the transmission and distribution of hydrogen through the existing natural gas infrastructure to the end-use applications of the residential and service sector. The hydrogen infrastructure configurations that are selected are hence based on the transportation of pure hydrogen through the natural gas infrastructure. Variations can exist in the production methods used (i.e. centralized versus decentralized) and the specific end-use equipment. The following two hydrogen infrastructure configurations are hence adopted from Bolat & Thiel (2014a):

1. Centralized hydrogen production  $\Rightarrow$  transmission pipeline network  $\Rightarrow$  distribution pipeline network  $\Rightarrow$  stationary end-use applications
2. Decentralized hydrogen production  $\Rightarrow$  distribution pipeline network  $\Rightarrow$  stationary end-use applications

These hydrogen infrastructure configurations are illustrated in Figure 26. The integration of these hydrogen infrastructure configurations in the Dutch natural gas infrastructure will be investigated in terms of their techno-operational and economic institutional implications for its functioning. Bolat & Thiel (2014a) identified seventeen other potential hydrogen infrastructure configurations. These configurations are either based on the transportation of liquified hydrogen or the blending of hydrogen

with natural gas. For that reason, these hydrogen infrastructure options are out of the scope of this thesis project.

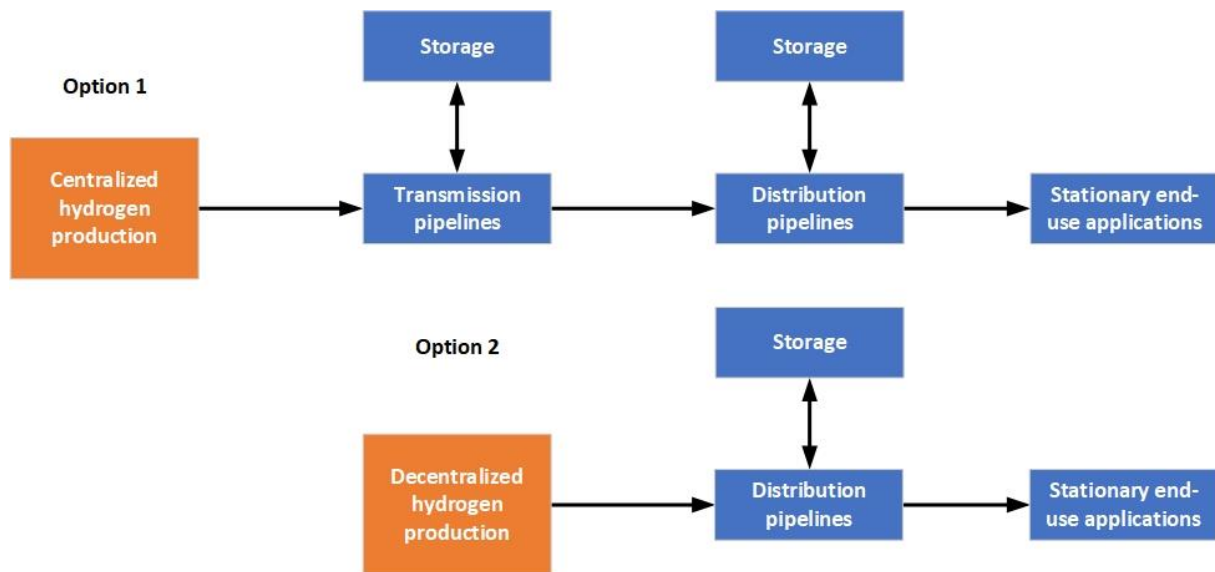


Figure 26: Hydrogen infrastructure configurations

Another potential hydrogen infrastructure configuration could be to produce hydrogen on-site at individual-scale. This would imply that no transmission or distribution networks for the transportation of hydrogen will be necessary. Decentralized water electrolysis would be a feasible hydrogen production technology. This hydrogen infrastructure will be left out of the scope of the thesis project since it implies that no gas grid connection is necessarily needed.

#### 4.2.1 Option 1: Centralized production

Option one includes an integration of hydrogen in the production, transmission, storage, and distribution segment of the natural gas infrastructure. The natural gas that is injected in the Dutch gas grid need to be replaced by hydrogen. Adequate amounts of hydrogen need to be produced centrally. The centralized produced hydrogen needs to be safely transported through the natural gas transmission networks. Hydrogen is stored in the underground natural gas facilities and distributed to the small-scale consumers by the existing distribution networks. The total demand of the distribution grid connections needs to be fulfilled by the utilization of hydrogen instead of natural gas. This means that the hydrogen transportation capacities of the transmission grid and the distribution grid should at least be large enough to replace the natural gas demand of the distribution grid connections. Whether the full transportation capacity of the transmission grid is substituted by hydrogen transportation capacity is not included in the scope of the thesis project. The assumption is made that if hydrogen replaces natural gas in a network, the replacement is conducted in the entire pipeline network system of a specific part of the network. This is assumed to exclude the operational problems of the admixture of natural gas and hydrogen. There are hence only limited possibilities of replacing natural gas by hydrogen in the Dutch natural gas grid.

The total annual demand of the consumers connected to the Dutch distribution grids (i.e. small-scale consumers) is approximately 21,8 billion cubic meters (Centraal Bureau voor Statistiek, 2018). This annual demand is the average annual demand over the period from 2010 to 2017. The Dutch households have an annual natural gas demand of approximately 8.9 billion cubic meters and the other small-scale consumers have an annual demand of 12,9 billion cubic meters. The total demand of the Dutch households is calculated by the following function:

Total annual demand of the Dutch households=

average annual natural gas demand from 2010 to 2017 \* total amount of households connected

The average annual natural gas demand from 2010 to 2017 is obtained from CBS (2018). The total amount of households connected is calculated by multiplying the percentage of households over the total building stock with the total amount of connections to the distribution grid. The total amount of connections to the distribution grid is obtained from Netbeheer Nederland (2018). The percentage of households over the total building stock is calculated by the data obtained from CBS (2019). The annual demand for natural gas from the households and other consumers corresponds with approximately 89 TWh and with approximately 113 TWh. In the demand calculations, it is assumed that the calorific value is corresponding with the G-gas equivalent of 31.65 MJ/m<sup>3</sup> (Centraal Bureau voor Statistiek, 2018).

The total average annual supply of natural gas is approximately 43.2 billion cubic meters (Centraal Bureau voor Statistiek, 2018). This corresponds with a total supply of approximately 361 TWh. The demand of the distribution grid connections is approximately 53 percent of the total demand and hence corresponds with an annual demand of 192 TWh. The latter annual gas demand needs to be satisfied by hydrogen. The amount of hydrogen that needs to be produced must correspond with the total annual demand of the distribution grid connections<sup>6</sup>. The capacity of the installed hydrogen production technologies must hence be adequate to satisfy the annual demand.

Hydrogen production methods need a capacity of approximately 27.4 GW. This capacity is calculated by the following function:

Hydrogen production capacity needed =

$$\frac{\frac{\text{annual demand of distribution grid connections}}{\text{average availability factor}}}{\text{hours in a year}}$$

The average availability factor is assumed to be 80%, based on the values in Table 9. The hydrogen production capacity needed, corresponds with approximately 25 coal gasification plants of 1500 MW. Large-scale coals gasification and large-scale steam methane reformation are currently reaching the highest capacities (Bolat & Thiel, 2014b). Centralized coal gasification and centralized steam reformation are currently the most cost-effective production methods (Bolat & Thiel, 2014b).

The total costs and emissions of producing the needed amount of hydrogen are calculated from the hydrogen production technology characteristics in Table 9 and the above calculated hydrogen demands. The total costs of 192 TWh of hydrogen are approximately in 6.8 billion euros. The hydrogen production costs are hence in between 5 to 47 €/GJ, depending on the specific hydrogen production technology. The annual CO<sub>2</sub> emissions of the different hydrogen production technologies are in between 50 and 194 Mton. The average natural gas price for Dutch households from the period of 2010 to 2017 was in between 12.1 and 20.6 €/GJ. Of this natural gas price, approximately 40 percent can be attributed to the production costs (Prieto & Correljé, 2017). This means that the production costs of natural gas are approximately 2 to 7.5 €/GJ. The annual CO<sub>2</sub> emissions of the natural gas consumption in buildings and installations is approximately 39 Mton. The relatively high emission levels of hydrogen production refer

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<sup>6</sup> The energy efficiency improvements of hydrogen over the use of natural gas are neglected. The effect of energy losses due to hydrogen leakages is assumed to be equal to the energy losses due to natural gas leakages.

to the need for CCS, fuel cells and the use of green primary energy sources in the production of hydrogen. The annual operational costs of a hydrogen grid are approximately 2 million euros per PJ following the calculations of CE Delft (Afman & Rooijers, 2017). The capital costs of adjusting the current natural gas grids to hydrogen grids are approximately 3 million euros per PJ (Afman & Rooijers, 2017).

#### 4.2.2 Option 2: Decentralized production

Option two implies a situation where natural gas is still the only energy carrier used in the transmission networks of the Dutch gas grid. Natural gas is transported to the areas of demand where hydrogen is produced on-site. Option two differs from option one in the use of the transmission grid. In option two, the transmission grid is still utilized to transport natural gas to the distribution grids and the large-scale consumers. The hydrogen production technologies will be in the beginning hence largely based on the use of steam methane reformation (i.e. natural gas). The produced hydrogen is distributed through the existing distribution networks. The distribution of the hydrogen in option two is hence like the distribution in option one. Other hydrogen production technologies can complement the steam methane reformation. Other than in option one, option two implies the use of more decentralized produced hydrogen. Large-scale steam reformation can still be applied to produce hydrogen centrally and distribute it to the consumers. Smaller-scale hydrogen production technologies can be utilized closer to the demand. When renewable energy generation options such as solar and wind become widely adopted, electrolysis will become a feasible option to replace the fossil fuel-based hydrogen production. The Dutch distribution grids are separately operated by the DSOs. The amount of natural gas that needs to be replaced is hence dependent on the demand of a specific distribution network. In the calculations on the distribution grid specific demands, it is assumed that the distribution of household and non-household buildings is equal among the various distribution grids. The distribution grid specific demands are calculated with the calorific value corresponding with the G-gas equivalent of 31.65 (Centraal Bureau voor Statistiek, 2018). This results in the following distribution grid demand shown in Table 10<sup>7</sup>.

Distribution grid operator	Demand [PJ]
Cogas Infra & Beheer B.V.	15.2
Enduris	20.6
Endinet	43.5
Enexis B.V.	225
Liander	244
N.V. Rendo	11.3
Stedin B.V.	212
Westland Infra	5.81

Table 10: Demand per DSO, adopted from Netbeheer Nederland (2018)

The capacities that are needed to satisfy the distribution grid specific demands are calculated. These calculations use the same availability factor as above (i.e. 80%). Table 11 shows the needed hydrogen production capacities per distribution grid.

<sup>7</sup> The energy efficiency improvements of hydrogen compared the use of natural gas are neglected in table 1 and table 2. Only the average demand and capacity is considered, the peak demand and peak capacity is not considered specificity.

Distribution grid operator	Capacity [GW]
Cogas Infra & Beheer B.V.	0.60
Enduris	0,82
Endinet	1.72
Enexis B.V.	8.94
Liander	9.68
N.V. Rendo	0.45
Stedin B.V.	8.40
Westland Infra	0.23

Table 11: Capacity per DSO

The total demand of natural gas that is replaced if all the distribution grids will be transferred to hydrogen grids equals the demand presented in option one. Hence, the same emission factor, and prices of natural gas are hence applicable. The difference in option two, regarding option one, is that decentralized production options and a partial adoption of hydrogen can lead to different outcomes in terms of CO<sup>2</sup> emissions and costs.

Centralized steam methane reformation has energy efficiencies ranging from 1.38 to 1.65 kW/kW H<sup>2</sup> (Bolat & Thiel, 2014b). This means that for every kW of hydrogen, 1.38 to 1.65 kW of natural gas is needed. If option two is totally based on steam methane reformation, it hence requires 1.38 to 1.65 times more transport capacity of the transmission grid compared to when natural gas is utilized in the distribution grids. On-site decentralized steam methane reformation technologies can potentially reach higher energy efficiencies, up to 0.9 kW/ kW H<sup>2</sup>. The capacities of these small-scale production technologies are much lower than the centralized production technologies. The capacities of small-scale steam methane reformation production technologies range from 14.6 to 70.7 MW. The smaller capacities would require many distributed smaller production plants. The latter makes the application of CCS more difficult and costlier.

The costs of the decentralized and centralized steam reformation technologies range respectively from 15 to 35 €/GJ and 18 to 25 €/GJ. The costs of decentralized and centralized electrolysis range respectively from 39 to 56 €/GJ and 38 to 47 €/GJ. The decentralized production of hydrogen is generally costlier. Although, there are possibilities where decentralized steam reformation can be more cost-effective than 18 €/GJ (Bolat & Thiel, 2014b).

### 4.3 Discussion on the presented characteristics of the hydrogen options

The calculations that are presented above as the characteristics of the two hydrogen options, central in the thesis project, are an oversimplification of the reality. These characteristics are presented to function as an indicator of the magnitude of replacing approximately 20 billion cubic meters of natural gas. In the calculations the assumption is made that the energy content connected to the latter volumes of natural gas is totally replaced by hydrogen. This oversimplification is made to discuss the challenge of replacing natural gas in terms of demand, production capacity, costs, and CO<sub>2</sub> emissions.

The demand for natural gas is unlikely to be entirely replaced by hydrogen. End-users will adapt other alternatives to natural gas such as all-electric, green gas, and district heating. Besides, insulation measures will further reduce the demand for energy in the built environment. Efficiency differences within the various alternatives to natural gas and hence within the calculation above are not included. With the inclusion of the effects of the diffusion of the other alternatives and the demand reductions of

insulation and efficiency gains, the demand for hydrogen will be significantly lower as presented above. The CE Delft report addresses the uncertainty of the diffusion of the different alternatives to natural gas, and presents four scenarios for the development of hydrogen in the built environment (Afman & Rooijers, 2017). In these scenarios the potential annual hydrogen supply varies from 0 PJ to 203,2 PJ (Hermkens et al., 2018). The four scenarios hence predict a role of hydrogen of respectively around 3, 37, 29, and 0 percent of the total low-temperature supply to the built environment. Hydrogen is hence not likely to replace the total natural gas demands (Hermkens et al., 2018). In the report of DNGVL, the maximum potential annual supply of hydrogen for low-temperature heat is estimated on 100 PJ (van den Noort et al., 2017). In the latter potential supply, only the households are included.

The production capacity, as described in option 1 and option 2, necessary to replace the demand for natural gas is hence also an oversimplification. The supply of energy for satisfying the heat demand of the built environment will be based on a variety of production technologies. In line with the results from the KIWA report and the DNGVL report described above, only a percentage of the total heat demand will be satisfied by hydrogen. Which percentage this will be is disputable.

The costs calculations are based on the theoretical costs of producing hydrogen adopted from Bolat & Thiel (2014b). Developments from external indicators as technical innovations, politics, and energy markets are not considered. Other studies could hence deviate from these hydrogen production costs. The total hydrogen production cost range, as presented in the calculations above, is based on the replacement of the total natural gas supply (i.e. approximately 700 PJ) by hydrogen. These costs hence represent the production costs of a situation in which hydrogen will replace the total natural gas demand. The latter is, as discussed in the previous paragraph, unlikely. The production costs will therefore be less than the calculated cost range. Moreover, the cost range is based on a variety of different production technologies. When specific production technologies are chosen in terms of production scale and technology the cost range can be calculated more precisely.

The CO<sub>2</sub> emissions per unit of hydrogen per hydrogen production technologies are adopted from several studies (Arvidsson et al., 2015; Man et al., 2014; Muradov, 2017). In analogy with the total annual cost calculations, the total annual CO<sub>2</sub> calculations are also using the total natural gas demand of approximately 700 PJ. Within the calculations of the CO<sub>2</sub> emissions the effects of CCS, the use of renewable electricity, and the technological developments are not considered. The latter could result in a rather high range of CO<sub>2</sub> emissions that represent the emissions of the so-called grey hydrogen. The emissions of blue hydrogen and green hydrogen production activities are not included in the calculations.

With the pitfalls of the calculations in mind, they still provide the broad context of the challenge of replacing approximately 20 billion cubic meters of natural gas. Since it is unsure what the developments in the hydrogen technology, demand, supply, and prices are, the calculations are not representing the real characteristics of replacing natural gas by hydrogen. Instead, the calculations provide insights in the magnitude of the challenge and the magnitude of the hydrogen infrastructure when it fully replaces natural gas.

## 5. Challenges of integrating hydrogen

This chapter addresses the questions, *what challenges does the integration of the hydrogen configurations have on the functioning of the natural gas infrastructure?* and *What are convenient alterations in the design of the natural gas infrastructure to deal with the challenges of the integration of the hydrogen infrastructure configurations?* These questions will be answered by the identification of the challenges that an integration of hydrogen poses. The challenges will be identified by investigating the change caused by the integration of the hydrogen options in the Dutch gas infrastructure. Change refers here to the components that need to be adjusted or added to the gas infrastructure design because of the integration of hydrogen. The comprehensive design framework will be consulted to analyze the change and the accompanying challenges that a hydrogen integration has on the functioning of the Dutch gas infrastructure. Main challenges will be derived, and a possible hydrogen infrastructure configuration will be discussed. The focus will be on the techno-operational and economic-institutional challenges of the integration of hydrogen. The identified change and design challenges are derived from the semi-structured interviews with hydrogen and natural gas experts (see section 9.2).

Section 5.1 elaborates on the change in the technical-operational dimension of the design of the gas infrastructure. Section 5.2 elaborates on the change in the economic-institutional dimension of the design of the gas infrastructure. Section 5.3 presents the challenges of the integration of the hydrogen infrastructure configurations in the various layers of the framework. Section 5.4 discusses the main challenges in the system design because of the integration of hydrogen. Section 5.5 discusses the main challenges in the economic institutions because of the integration of hydrogen. Section 5.6 present a hydrogen infrastructure option that can be integrated and discusses the dominant design choices. Section 5.7 concludes with an assessment of alignment regarding the technological and institutional changes in the gas infrastructure.

### 5.1 Change in the design variables in the gas infrastructure

The system design of the gas infrastructure refers to the design perspectives, the design principles and the control mechanisms (Scholten & Künneke, 2016). Figure 27 illustrates the three layers of design variables. This section will elaborate on the changes in the design of the specific variables within these three layers because of the integration of hydrogen.

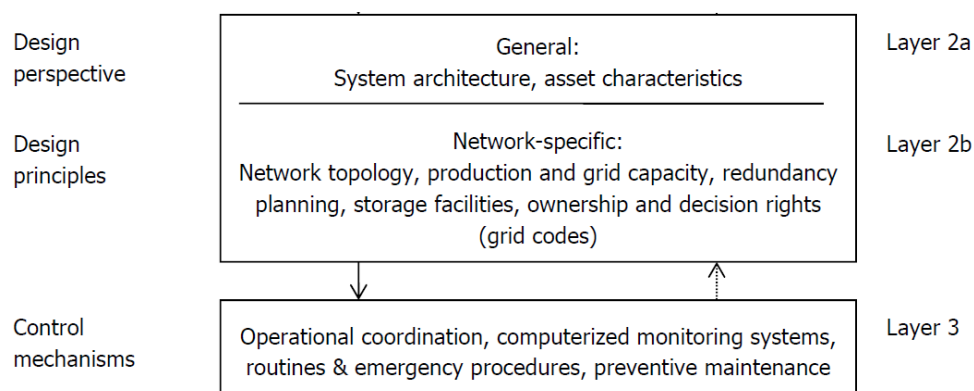


Figure 27: Layer 2a, layer 2b, and layer 3 of design variables in energy infrastructures, adopted from Scholten & Künneke (2016, p.10)

#### 5.1.1 System architecture

Change in the system architecture is dominantly caused by the new hydrogen production segment. Gas from different qualities needs to be produced, transported, stored, and consumed within the current gas

infrastructure. The gas production changes from a mining activity to a conversion activity in which several conversion technologies, based on different energy sources, are possible. The possibility of the decentralized production of hydrogen implies that the supply of gas will occur more locally. Because of the nature of the hydrogen production and the possibilities for the local production of hydrogen, the interactions between the producers, system operators, consumers and storage operators change.

#### **5.1.1.1 New production segment of gas**

The hydrogen production will largely be based on the production of green hydrogen from renewable energy and biomass, and the production of blue hydrogen, mainly from natural gas. Grey hydrogen is not an adequate replacement of natural gas in terms of the CO<sub>2</sub> that is emitted. The production segment of hydrogen is more intertwined with other sectors compared to the natural gas production segment. The production of blue hydrogen requires an interaction with CCS infrastructure. The production of green hydrogen through electrolysis requires an interaction with the electricity sector and the production of green hydrogen from biomass requires an interaction with the biomass sector, comparable as with the production of biogas. Steam reformation and gasification include by-products that can be used as feedstock for the industry, which implies an interaction with the industry. The production of gas is hence no longer bounded to the geographical existence of natural gas fields, more producers can emerge that are willing to inject hydrogen gas into the public grids from various locations and from different gas qualities. The system architecture can become more open to a broader variety of interactions with producers and other systems. It needs to be determined how the gas system interacts with the other systems and which production technologies can emerge where in the system. The physical and operational constraints of the public grids are therewith important.

The centralized production of hydrogen gas (i.e. hydrogen option 1<sup>8</sup>) will not significantly change the interaction between the transmission, storage, and distribution grids. The decentralized production of hydrogen gas (i.e. hydrogen option 2<sup>9</sup>) will pose more change to the system architecture. In analogy with the production of biogas, hydrogen gas can be produced more locally. The locally available biomass, natural gas and electricity can be used to produce hydrogen and therewith to satisfy the local energy demand. Moreover, locally produced hydrogen can be injected in the public grids. The former notion implies that gas can be consumed without intervention of the public grids and the latter notion that the public grids need to be able to interact with larger volumes of locally produced gas. When the locally produced gas is injected in the distribution grids and needs to be transported to the transmission grids, the system architecture needs to change from a system that functions with a unidirectional flow of gas to a system with a bidirectional flow of gas.

#### **5.1.1.2 Organization of buffer capacity**

The natural gas reserves in the Groningen field, the import capacity, and the storage capacity in the Netherlands determine the buffer capacity in the Netherlands. When hydrogen is produced from natural gas, wind, solar, and biomass, the buffer capacity is determined by the availability of these resources, the production processes of the concerned production technologies, the hydrogen import capacity, and the hydrogen storage capacity. Per hydrogen production technology, the buffer capacity differs due to the availability and storability of the energy input and the possibilities of the production technologies to be scaled up and down. Option 1 will not significantly change the system architecture if the underground storage facilities will be adapted for the underground storage of hydrogen. Hydrogen can be produced centrally and stored centrally, only the underground storage facilities change in characteristics and

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<sup>8</sup> Option 1 as introduced in chapter 4, from now one called “option 1”.

<sup>9</sup> Option 2 as introduced in chapter 4, from now one called “option 2”.



capacity. Option 2 implies a choice between the local storage of hydrogen (i.e. nearby the local production of hydrogen) and the injection of hydrogen in the public grids to be stored centrally. When the supply of the locally produced hydrogen exceeds the demand but is not stored locally, it will change the system architecture. Hydrogen need to be supplied to the transmission grids. The latter requires the transmission grids to interact with the distribution grids differently. Hydrogen gas needs to be transported from the distribution grids to the centralized storage facilities or consumers. When hydrogen is stored locally, a variety and substantial number of storage locations need to interact with the distribution grids. The latter would move a part of the buffer capacity to the local storage facilities and hence to the distribution grids. The large-scale and more centralized storage facilities will still be needed to satisfy the total need for buffer capacity (i.e. especially the seasonal fluctuations in the demand). The combination of decentral and central storage facilities will change the way that the buffer capacity is organized, especially looking at the day-to-day balancing of supply and demand in the distribution grid. The decentral storage facilities will introduce a new storage segment.

#### **5.1.1.3 Emergence of micro-grids**

Micro-grids refer to the pipeline networks that are operated apart from the public grids. These networks connect local gas producers to local consumers and are mostly privately owned and operated. The system architecture of the gas infrastructure changes when these hydrogen micro-grids need to interact with the public grids. Basically, these grids can be considered as decentralized producers when they want to inject hydrogen in the distribution grids and as consumers when they want to withdrawal. Micro-grids can also function as a storage operator when they allow for the storage of the local hydrogen supply. The interaction between the distribution grids and these local grids change the system architecture of the gas infrastructure due to the dynamics of entities that are local producers, consumers, and possibly storage operators. It needs to be determined whether it is desirable if such micro-grids occur apart from the public grids.

#### **5.1.1.4 The interaction between the gas and electricity systems**

Currently natural gas is used to produce electricity. In a hydrogen infrastructure electricity will also be used to produce hydrogen. The latter implies that the energy content of electricity and gas can change from energy carrier at various locations in the systems. The transformation of electricity to hydrogen makes electricity and hence renewable energy such as wind and solar energy storable. Wind and solar energy can be used to produce both electricity and hydrogen. Wind and solar energy could be transported over longer distances in the form of hydrogen. The end-use segment in the residential and service sector can use hydrogen to satisfy both the heat demand and to produce electricity by means of a fuel cell. The Hydrogen and electricity sector hence become more interchangeable in the provision energy. The latter can fundamentally change the system architecture of the gas infrastructure.

#### **5.1.2 Asset characteristics**

The assets involved in the transmission, storage, distribution, and consumption of natural gas are compatible with natural gas. For the integration of hydrogen, new assets need to be introduced to produce hydrogen. Next to these hydrogen production assets, the existing assets need to be compatible to utilize hydrogen.

#### **5.1.1.5 Hydrogen production assets**

Hydrogen production has a negative energetic efficiency in terms of the hydrogen output. With hydrogen as a replacement of natural gas, it is desirable to produce blue or green hydrogen. The production of blue hydrogen is based on the production of hydrogen from fossil fuels including an extra CCS step.

The production of green hydrogen is either based on green electricity or biomass as energy input. The production of blue hydrogen will play a key role in the short-term due to the lack of available green or blue electricity and biomass.

#### **5.1.1.6 Hydrogen pipeline networks**

Hydrogen can have negative effects on the fatigue of steel pipelines that are operated under changing pressures and hence reduces the life span of the pipelines (van den Noort et al., 2017). The fatigue crack growth becomes a factor 10 higher than with natural gas (van den Noort et al., 2017). Hydrogen embrittlement of the steel in the pipelines will only occur if the relative humidity of the hydrogen exceeds 60% (van den Noort et al., 2017). Because of the smaller density of hydrogen compared to natural gas (i.e. 85.5 with respect to 678.6 g/m<sup>3</sup> at normal pressure and temperature) hydrogen leakages involve a factor 2.8 more volume than natural gas leakages (van den Noort et al., 2017). The energy content involved in the leakages will almost be equal because of the calorific values (35 with respect to 11 MJ/m<sup>3</sup> at 1 atm). Leakage from the fittings of the pipes are causing a flow rate of 25 percent higher with hydrogen than with natural gas (Hermkens et al., 2018). Pipelines made from synthetic material suffer from permeation. Permeation refers to the permeation of water vapor, nitrogen, and oxygen from the outside air through the walls of the synthetic pipelines. Hydrogen permeates 5 times faster through the synthetic materials than natural gas (Hermkens et al., 2018). Permeation is dependent on the temperature, the pressure, the properties of the material, and the construction methods of the pipeline network. Next to the synthetic pipelines, synthetic materials are also used as packings, gaskets, and membranes. Micro-organisms can cause corrosion in the pipelines. With low pressures, and dry conditions (i.e.  $P_{max} < 8$  bar and  $T_{max} < 18$  °C), microorganisms are not likely to exist (Hermkens et al., 2018). Metering stations must be adjusted to be compatible with the higher gas flow rates and the different gas qualities.

Compression stations in the transmission grids are not compatible with hydrogen. Hydrogen requires a factor three times larger volume to transport the same energy content (van den Noort et al., 2017). The centrifugal compressors in the grid are not designed to operate with these higher flow rates and would require a rotation speed of 1.74 times higher than currently applicable with natural gas (van den Noort et al., 2017). The reciprocating compressors are also not compatible with hydrogen. Compression stations that are based on gas turbines need to be replaced or adjusted to the use of hydrogen or electricity instead of natural gas.

Pressure reduction stations will not need their gas heating abilities anymore. Hydrogen has a small and negative Joule-Thomson coefficient compared to the larger and positive coefficient of natural gas (van den Noort et al., 2017). With pressure reductions from 80 to 20 bar, hydrogen will increase in temperature with approximately 2.1 °C (van den Noort et al., 2017). Natural gas increases with the same temperature reduction with approximately 30 °C (van den Noort et al., 2017). The cooling of natural gas at the at the compression stations is hence not necessary anymore.

Hydrogen needs eight times the pressure of natural gas to be stored in the same mass in a same cubic (Bai et al., 2014). The well integrity of the underground storage facilities needs to be adjusted to the properties of hydrogen and the materials present in the underground gas storage vessel need to be compatible with hydrogen. Hydrogen in depleted gas reservoirs can be problematic because of the existence of cushion gas. When hydrogen interacts with cushion gas they easily mix, resulting in impure hydrogen (Bai et al., 2014). Other problems can be caused by the possibility of chemical reactions between hydrogen and sulfide minerals, sulfate, and carbonate (Bai et al., 2014). The latter can cause toxic acid gasses to be formed such as H<sub>2</sub>S, SO<sub>2</sub>, and CO<sub>2</sub> (Bai et al., 2014).

### **5.1.1.7 Hydrogen end-use applications in the built environment**

The options for end-use applications of hydrogen in the built environment are based on the combustion of hydrogen or on the utilization of hydrogen in a fuel cell. The combustion rate of hydrogen is significantly higher than the one of natural gas (Hermkens et al., 2018). Natural gas combustion equipment such as the natural gas condensing boiler needs to be replaced or adjusted to be compatible with hydrogen. The main adjustments that need to be made are the application of another security system and the adjustment of the materials (Hermkens et al., 2018). When hydrogen is to be utilized in fuel cells, high purity requirements need to be satisfied. The latter will imply a cleaning step right before the hydrogen enters the fuel cells or the transportation of hydrogen in high purity levels (Hermkens et al., 2018). The hydrogen condensing boilers do not have these high purity requirements.

### **5.1.3 Network topology**

The network topology mainly needs to change because of the new production segment that is integrated. In option 1, centralized production facilities must be strategically sited within the constraints of the gas grid regarding the network topology. The transmission network should be converted to satisfy the distribution grid gas demand, plus a safety range. The latter means that the current natural gas infrastructure need to be redesigned for the purpose of the injection, transportation, storage, and withdrawal of a specific amount of hydrogen gas. The choice on the amount of hydrogen transportation capacity is essential for the network topology of the gas grid. A 100 percent conversion to hydrogen would require all the transportation, storage, and end-use applications of the natural gas transmission grid to be adjusted to hydrogen. This means that all the connections to the grids and the accompanying equipment need to be adjusted to hydrogen. A scenario where for example 60 percent of the transmission grid will be transformed implies significant changes in the way in which the network topology of the transmission grid is designed. The transmission pipeline systems need to be allocated to transport gas in different qualities. Moreover, network entry and exit points to neighboring countries, other transmission networks, end-users, and storage facilities need to be allocated to a specific gas quality. The latter introduces a large challenge for the operational coordination of the grid and the coordination of its customers.

The transformation of the distribution grid in option two implies, in analogy with option 1, the transformation of an entire distribution network. The latter refers to the adjustments in the distribution, storage, and end-use assets. Option 2, however, relies largely on the on-site production of hydrogen instead of the hydrogen supply from the transmission grid. The on-site production refers to the production of hydrogen nearby the area of demand. Whether this implies the integration of large-scale production facilities that distribute hydrogen through the distribution grid or many small-scale hydrogen production facilities nearby the actual buildings are important questions. The large-scale production facilities will not change much in the distribution network topology since they can replace the injection from the transmission grids (i.e. or function is a similar fashion). The small-scale production and injection of hydrogen gas imply significant changes in how the grid is operated and how the topology is designed. Customers of the distribution grids can become producers and storage operators. Important is to determine if the network topology of the distribution grid needs to be based on the principle of a centralized topology (i.e. in which the gas flow is connected to centralized hub of production) or on a more decentralized network topology (i.e. in which the gas flow is connected to several decentralized production units). The new emerging producers need to be connected to the public grids based on their specific production capacities. Large volumes of hydrogen gas can only be injected in the higher-pressure grids, which require new pipelines to be constructed or require production facilities to be sited

differently. When the gas is injected in the lower-pressure grids and needs to flow to the higher-pressure grids, boosters need to be installed to allow for the bilateral flow of gas. The latter will result in a more complex network topology and operation, the capital and operational costs of the networks will increase.

CCS infrastructure is needed to decarbonize the hydrogen gas provision on the short-term. For the decentralized production of hydrogen, it will be hard to integrate CCS in the network topology of the distribution grids. CCS infrastructure needs to include pipeline networks to transport the CO<sub>2</sub> and storage facilities to store the CO<sub>2</sub>. The latter infrastructure requires space and the presence of an underground CO<sub>2</sub> storage facility. The network topology would become more complex and costly if a comprehensive pipeline network of CO<sub>2</sub> emerges for the transport of CO<sub>2</sub> over longer distances. CCS infrastructure hence is more likely to be sited nearby its production and consumption. The siting of green hydrogen production facilities is dependent on the availability of renewable energy production facilities and on the possibilities to store the energy surplus in the form of hydrogen. The location of the gas production facilities becomes hence less dependent on the availability of natural gas and can be sited in various locations.

#### **5.1.4 Production, storage and grid capacity**

The hydrogen production capacity that needs to be in place to replace the total distribution grid demand for natural gas by hydrogen is approximately 30GW. The current hydrogen production capacity in the Netherlands is approximately 5GW and used in the industry (van den Noort et al., 2017). Currently, the Groningen field is providing approximately 50 percent of the total natural gas production (Centraal Bureau voor Statistiek, 2018; Nederlandse Aardolie Maatschappij, 2018). The daily peak capacity of the Groningen field is approximately 350 million cubic meters (NAM, 2018). This peak capacity corresponds with a hydrogen production capacity of approximately 160 GW. The latter represents an extraordinarily large production capacity and hence provides a very flexible gas supply that can be scaled up and down. The production capacity of hydrogen will be dependent on the production plants that need to be installed. The average capacity that is needed to replace all the natural gas supply in the Netherlands without accounting for peak load capacity would approximately be 52 GW. Next to the flexibility, the Groningen gas field and the smaller gas fields contain enormous volumes of gas reserves, i.e. approximately 1000 billion cubic meters (CBS, 2018a). When hydrogen is produced from renewable energy through electrolysis, these gas reserves need to be compensated through the underground storage of hydrogen. Currently, the underground storage facilities of natural gas have a capacity of approximately 14 billion cubic meters (Energy Stock, 2019; International energy agency, 2008; NAM, 2019; TAQA Energy, 2019). If these storage facilities will be converted to hydrogen storage facilities less energy can be stored due to the smaller volumetric energy density of hydrogen compared to natural gas. When hydrogen is produced from natural gas, these gas reserves can be used. The overall installed hydrogen production capacity will hence be the constraining factor in terms of output and flexibility of hydrogen produced from natural gas. The hydrogen production will be significantly less flexible than the production of natural gas and will include significantly lower production volumes on the short-term. If hydrogen is to be widely adopted by the end-users in the built environment, it is unavoidable to install large-scale hydrogen production and storage facilities to satisfy the demand.

The transportation capacity is dependent on the gas flow rate of hydrogen. Due to the smaller energy density of hydrogen compared to natural gas, hydrogen basically needs a gas flow rate of approximately three times higher than natural gas to transport the same energy content (van den Noort et al., 2017). Figure 28 illustrates the transport capacity of 100 percent hydrogen compared to natural gas. At a fixed pressure drop, pure hydrogen is able to transport 98 percent of the energy content through the low

calorific pipeline networks, and 80 percent through the high calorific network (van den Noort et al., 2017).

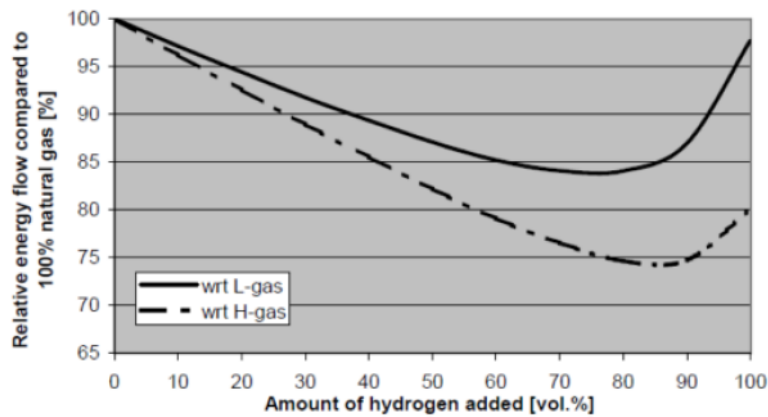


Figure 28: Transport capacity of pure hydrogen compared to natural gas for both the low calorific and high calorific transmission grids, adopted from van den Noort et al. (2017)

Storage capacity, in analogy with transport capacity, also requires three times more volume of hydrogen to store the same energy content compared to natural gas. This hence requires more storage capacity underground if hydrogen is to be stored in gaseous form. Linepacking storage includes the same principle in terms of the larger volumes needed which is illustrated in Figure 29.

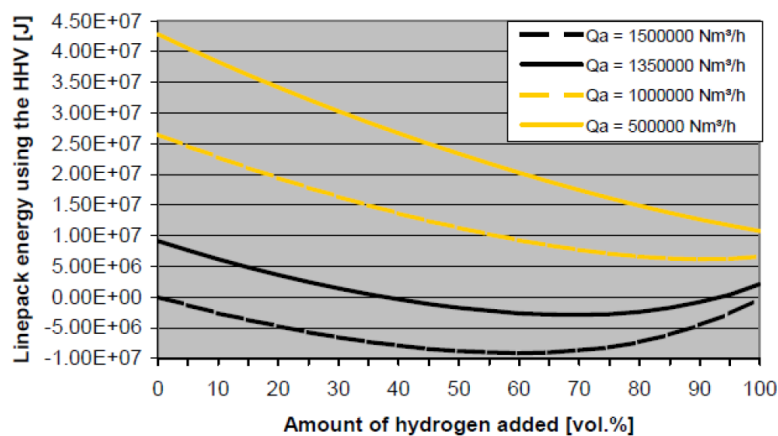


Figure 29: linepack energy content including various gas flow rates, adopted from van den Noort et al. (2017)

### 5.1.5 Redundancy planning

The assets present in the natural gas transmission and distribution pipeline networks are generally designed based on the N+1 criterion. It could be possible that the assets in the gas infrastructure require a more intensive redundancy planning based on the effects that the use of hydrogen, and the use of different operational pressures and temperatures has on the materials of the assets. Whether the current redundancy planning regime is adequate to ensure the reliability of the hydrogen transportation needs to be investigated. When hydrogen is produced decentral, redundancy requirements can pose larger investment costs due to the more intensive use of the distribution grids. No more intensive redundancy planning is probably necessary since the Dutch gas grid is already reliable and insulation measure in the connected buildings will increase (i.e. less severe consequences of interruptions).

### 5.1.6 Ownership and decision rights

Ownership and decision rights regarding the hydrogen assets in the production, transmission, storage, distribution and consumption segments of the infrastructure need to be defined and allocated to the

various actors. The large-scale injection of hydrogen gas in the public grids is new and no gas standards are formulated yet. The gas quality standards for the transmission and distribution grids need to be controlled by the system operators. The hydrogen production and consumption assets need to be compatible with these standards. The Gas Act currently does not allow the system operators to participate in any activity not related to the provision of natural gas. The latter needs to be changed in the Gas Act for the system operators to become active in the provision of hydrogen. The nature of the hydrogen production allows hydrogen to be converted from a variety of sources in a variety of places. It needs to be defined which conversion processes can be conducted by which entities. Ownership and decision rights regarding the different hydrogen production technologies need to be defined. Large-scale steam methane reformation plants including CCS infrastructure have for example different operational requirements than small-scale decentralized electrolyzers. For every different production asset, clear ownership and decision rights need to be defined. Ownership and decision rights regarding the transmission, storage, and distribution grids can generally stay the same (i.e. taking the changing hydrogen gas properties in consideration). Compared to the natural gas production segment, the hydrogen production assets have no direct need to include public-private ownership rights and there is no need to interfere in the production decisions, apart from security of supply considerations.

### **5.1.7 Operational coordination**

The current balancing regime of GTS and the DSOs need to be reconsidered due to the possible higher gas flow rate and changing hydrogen volumes in the grids. The line-packing flexibility in terms of energy content decreases for example because of the higher gas flow rates, see Figure 29. A lower hydrogen demand in the built environment, compared to the natural gas demand, can increase the line-packing flexibility again. The damping formula of GTS needs to be adjusted to the higher gas flow rates and the lower energy content. The models used by the system operators to allocate the transport capacities need to accommodate these new dynamics. THT, the odorant that is added to natural gas before it enters the distribution grid is not compatible within an admixture of hydrogen since it contains sulfur.

Option 2 requires compared to option 1 a more intensive coordination mechanism due to the emergence of the decentralized producers that want to inject their gas into the distribution grids. Currently the distribution grids are predominantly supplied by the transmission grids. A marginal volume of biogas is locally produced and injected. With a larger share of decentralized production volumes of hydrogen gas, the balancing role of the DSO would become more intensive. Especially if the supply of gas to the distribution grids exceeds the demand. Decentralized producers of biogas, in the current situation, cannot inject their green gas if there is not enough demand. Local producers in such a situation are currently shut down. It needs to be determined whether such a supply mechanism is desirable. Green hydrogen could for example get the priority over blue and grey hydrogen or locally produced hydrogen could get the priority over the supply of the transmission grid. Important is to determine how the operational coordination of the variety of suppliers will be coordinated. When locally produced gas needs to flow to the transmission grids, both the transmission and distribution grids need to be able to facilitate a bidirectional flow. Boosters or other pipeline networks need to be installed and adequately dimensioned to facilitate the bidirectional flow of gas. The day-to-day balancing role of the DSOs in such a situation becomes much more intensive and complex. The local injection needs to be monitored and controlled in terms of the gas quality, the volumes, and the operational handling in the grid. The latter requires a much more intensive coordination role of the DSOs. The operational coordination between the transmission and distribution grids becomes also more intensive due to a bidirectional flow between the grids. A gas grids with a bidirectional flow between the distribution and transmission grids becomes much more cost intensive in terms of capital and operational costs than the current natural gas grid.

### **5.1.8 Routines, emergency procedures, and preventive maintenance**

Hydrogen has other properties than natural gas and hence requires the routines, emergency procedures, and preventive maintenance activities to be adjusted to these properties. The properties of hydrogen include some potential safety hazards. Potential hazards can be caused due to:

- the smaller density of hydrogen compared to natural gas,
- the lower ignition value,
- the higher gas flow rates necessary to transport the same energy content,
- the larger flammability and explosive limits in air,
- the effects of hydrogen on the materials in the gas grids and the accompanying assets,
- the chance that atomic hydrogen is being formed,
- impurities in the hydrogen, and
- the formation of micro-organisms.

The above-mentioned risks can cause potential safety hazards to occur. These hazards can be mitigated or prevented by safety routines, emergency procedures, and preventive maintenance. Important is that the system operators adjust their development, operational, and maintenance activities to the new requirements of the grid. Messaoudani, Rigas, Binti Hamid, & Che Hassan (2016) identify potential prevention and mitigation measures for the utilization of hydrogen in pipeline networks. Prevention measures are mainly aimed at adjusting the design of the physical infrastructure and the management of the operations to safely transport hydrogen (Messaoudani et al., 2016). Mitigation measures are aimed at the implementation of safety valves and barrier walls (Messaoudani et al., 2016). Safety valves will basically cut off the damaged pipelines and barrier walls are mitigating the effect of the jet flames that can occur when hydrogen leaks (Messaoudani et al., 2016). The early detection of potential hazardous situations is key in preventing them from happening. Existing detection devices, gas chromatography, flame ionization detection, and thermal conduction sensors may not be compatible to pure hydrogen (Messaoudani et al., 2016). These detection devices hence need to be tested and replaced where necessary. The marking of the pipeline networks to prevent damage by third parties becomes more important due to the potentially higher risks for safety hazards because of leakages. Currently the main cause of pipeline damage is the accidental interference of third parties with the pipeline networks.

Safety instructions currently exist regarding the natural gas and biogas provision and the accompanying working activities, which are respectively called VIAG, and VI-Biogas. These safety instructions exist to ensure a safe management of the public grids and hence the safe functioning of the gas provision systems. All system operators, contractors, and metering companies need to follow these safety instructions where they interact with the public grids. These safety instructions need to be newly formulated for hydrogen. A large share of these instructions is already compatible with the provision of hydrogen.

## **5.2 Change in the economic-institutions of the gas infrastructure**

The economic institutions of the gas infrastructure refer to the formal institutions, the governance arrangements, and the organization of the transactions between actors (Scholten & Künneke, 2016). Figure 30 illustrates the three layers of economic institutions that are “designable”. This section will elaborate on the changes in the design of the specific variables within these three layers because of the integration of hydrogen.

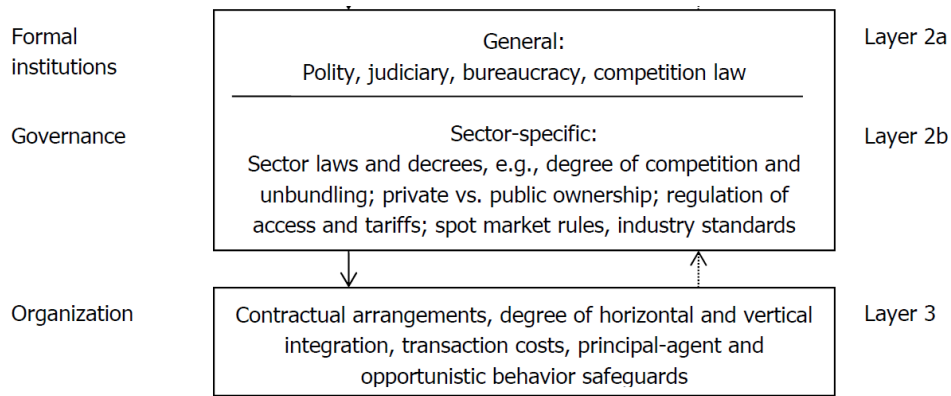


Figure 30: Layer 2a, layer 2b, and layer 3 of economic institutions in energy infrastructures, adopted from Scholten & Künneke (2016, p.12)

### 5.2.1 Formal institutions

An important choice is whether the conversion (or production) of hydrogen will be stated in the formal institutions as a production or as a conversion process. Both classifications include different tax structures which imply different tariffs for hydrogen. Moreover, current gas conversion activities (i.e. blending activities) are conducted by the system operators as a service. It is important to determine which hydrogen conversion activities are commercial activities and if system operators can participate in hydrogen production and conversion activities.

The production of hydrogen is not dependent on the extraction of gas but on the availability of production capacity and energy input, and hence would not require a public-private partnership. Hydrogen production facilities can be much more like power plants. Competition will not be based on the extraction permits and the lowest extraction costs but on the lowest price for the energy input of the hydrogen production process and the lowest operational and capital costs of the facilities. Regulatory entry barriers to the production of hydrogen could hence be less strict. Hydrogen can potentially be produced by a variety of parties at various locations. The storage at these locations might be cost-effective, e.g. due to low prices of renewable energy surplus. A fundamental choice is whether the wholesale market should facilitate all the transactions of gas between producers and customers or whether the retail market should also provide the transactions between producers and end-users in the built environment. The retail market design would need to change to provide the transactions between local producers and retail suppliers. Currently it is not possible for local producers without a supply permit to supply the consumers in the built environment. The gas needs to be transacted on the wholesale market or supplied through a private grid.

The spot market of natural gas currently allows for the trading of the volumes of natural gas that are present within the national transmission grid. In the short-term, such a spot market cannot be established for hydrogen. Large volumes of hydrogen need to be available and the market should provide enough safety mechanisms to earn back the large-scale investments in hydrogen assets. Bilateral-contracts will hence need to play a key role on the short-term. In a wholesale market with enough hydrogen supply, hydrogen gas can be traded in kWh alongside natural gas, irrespective of the energy carrier. In such a system, strict gas quality standards in the public grids can still facilitate the market functioning and the operational coordination of the grid. Energy companies are still able to trade energy, only the transportation capacity is constrained by the physical capacity of the grid. From a market viewpoint, only the energy carrier would change.



The demand for heat in the built environment can be replaced by other alternatives than gas. A main issue is whether end-users can choose which alternative energy carrier they can utilize and whether they are able to switch frequently. Currently, the Dutch policy regarding the energy strategies is already shifting the individual choice of end-users to the municipal level. From a system cost perspective, it can hence be more efficient to further infringe the consumer sovereignty to a national level. The latter would fundamentally change the way in which energy is provided to the built environment since the provision of energy would become the service and not the provision of an individual energy carrier. The retail segment would fundamentally change and need to be organized differently. Without consumer sovereignty, with respect to a specific energy carrier, it would not necessarily mean that no competition is possible. Competition can still be possible but on the level of energy content. Currently in the retail market, gas is traded in a similar fashion. Consumers are bounded to their gas connection and can only switch from retail supplier. In an integrated energy system, the relationship between the electricity and gas grids would change fundamentally. Laws and regulations regarding the specific grids need to be converged. The distribution grids will hence form a general energy distribution network instead of an individual electricity, gas, or district heating network. Investments in such a system can be made based on a total system efficiency instead on an individual system efficiency. The drawback of such a system is that end-users in the built environment will not have a choice in a specific energy carrier if they want to be connected to the public grids.

The choices of the government in what needs to change regarding competition, ownership, and regulation in the energy systems will determine to a large extent how the system will emerge. The possibilities of competition between various energy systems will determine to a large extent how the heat supply in the built environment will be satisfied. Important is to consider how a future energy system needs to function and especially what goals the system needs to address. With a priority on environmental goals, other choices could be relevant than with a priority on more economic goals. The boundaries of a new future energy system need to be formulated by the government. The laws and regulations that currently exist or that will be formulated can include undesirable lock-in effects.

### **5.2.2 Liberalization and unbundling**

The expectation is that the production segment can become more liberalized since the production of hydrogen does not include mining activities. This allows the hydrogen production segment to be liberalized further than the natural gas production segment. Mining companies can become active in the storage of CO<sub>2</sub> and stay active in the storage and extraction of natural gas. The delineation of the blue hydrogen production activities from the CO<sub>2</sub> and natural gas mining and storage activities needs to be defined. CCS needs to be applied directly in the production process, which would make it convenient for a hydrogen producer to actively work together with a storage operator of CO<sub>2</sub> storage facilities. The natural gas and CO<sub>2</sub> storage and extraction activities are already regulated by the Mining Act. The latter act does not include the storage of hydrogen. It needs to be determined how these activities will be regulated in terms of their interrelatedness and dependencies.

The system operators are currently not allowed to be involved in gas extraction activities but are involved in gas blending activities (i.e. conversion activities). In analogy with the conversion of H-gas to G-gas, steam methane reformation can be considered a process in which the gas quality is converted. From such a viewpoint, it can be argued that system operators can participate in the production of gas. System operators are currently not allowed to participate in any hydrogen related activities. Moreover, they cannot participate in any commercially related activities such as the production of gas. In analogy with the transportation services, these conversion activities can become a public service that is transacted for fixed tariffs (i.e. established by ACM). The latter would imply that on the one hand, the production

segment of hydrogen will become more liberalized by the variety of private parties that can produce hydrogen. On the other hand, a part of the production capacity can be owned and operated by the public system operators and will be more regulated.

### **5.2.3 Access regulation**

The Dutch Gas Act and the energy codes need to be adjusted to provide the public system operators with access to hydrogen related activities. It needs to be determined which actors (i.e. public or private) under what conditions can access the production segment of hydrogen. Different hydrogen production scales and technologies are possible. The latter requires new conditions to be formed for the various characteristics of the hydrogen production technologies. These conditions need to be monitored and controlled by a supervisory body. Permits can for example be necessary for large hydrogen production plants. Less intensive permits might be adequate for local hydrogen conversion units at the level of households. Hydrogen storage facilities can also be based on a variety of storage technologies. The underground storage of hydrogen can be regulated in a similar as with natural gas. The Mining Act needs to allow for the underground storage of hydrogen and the SodM needs to adopt the monitor and control activities. For other forms of storage activities, it needs to be determined which actors (i.e. public or private) subject to what conditions can participate in the various storage activities. Access regulation will become important in the emergence of hydrogen producers, storage operators and consumers. With high entry barriers it will be unlikely that companies will invest in the hydrogen sector. It needs to be determined whether the shipper access model is adequate for a hydrogen market and whether the gas supply permits need to be re-issued to retail suppliers that want to supply hydrogen to end-users.

### **5.2.4 Cost and Tariff structure**

The various hydrogen production technologies and the joint cost structures can make it hard to determine the actual cost price of hydrogen gas. The cost structure is hence depended on the costs of the primary energy source and on the prices of the various outputs of the hydrogen production processes, which can be both highly volatile. The production costs of grey hydrogen will be higher than the production costs of fossil fuels since they include an extra conversion step. The production of blue hydrogen includes next to the conversion step also the costs of including CCS in the production process. The production of green hydrogen is also dependent on an extra conversion step of electricity and currently expensive due to the high capital costs of the production plants (i.e. electrolyzers).

The tariff structure of hydrogen needs to be formulated in a way that the capital and operational costs of the infrastructure can be covered. Simultaneously, consumers need to be protected from unfair prices. The tariff structure of hydrogen should be competitive with its substitutes and simultaneously adequate to incentivize the needed investments. The latter requires the government to provide a tariff structure of energy that both mitigates the uncertainty of the investments and protects the consumers from unfair prices. This implies that not only the tariff structure of hydrogen needs to be defined, but the tariff structure of the other energy carriers needs to be redefined. Important is to determine how the price of hydrogen is to be established in a future hydrogen system. The current natural gas price is determined by the national and international gas markets. External price indicators from substitutes and other energy markets also contribute to the price forming of natural gas. Hydrogen requires another pricing mechanism since the market for hydrogen will not emerge on the short-term. Moreover, the gas infrastructure will become more capital costs intensive due to the large-scale investments that are needed. The price of hydrogen gas can hence never compete with the current energy prices on the short-term. The choice in tariff structure cannot be made in isolation from the other energy prices and taxes

that are applicable to the energy provision in the built environment. This introduces a complex interaction of hydrogen with the already mature energy markets in place.

The tariff structures of the various energy carriers throughout their supply chains can be influenced by the government by means of energy taxes. The energy taxes hence provide the government with a powerful instrument to determine which energy production, transportation, storage, and end-use assets will be attractive. Energy prices can be regulated in such a way that only the desired hydrogen production and end-use technologies emerge. The latter is difficult for a country to conduct in isolation due to the global nature of the energy markets.

### **5.2.5 Ownership and decision rights**

Ownership and decision rights regarding hydrogen infrastructures such as with natural gas are currently not yet defined since no comprehensive hydrogen infrastructure exists. The hydrogen infrastructure that is installed in the Netherlands is based on the privately owned and operated production, transportation, and end-use. Ownership and decision right regarding the provision of hydrogen through the public grids are currently not specifically defined.

The natural gas infrastructure already includes a comprehensive set of laws and regulations that define the ownership and decision rights regarding the various roles and responsibilities within the infrastructure. A large share of the ownership and decision rights applicable to the natural gas infrastructure can be adopted when hydrogen is integrated as an energy carrier in the gas infrastructure. Ownership and decision rights regarding the hydrogen production assets need to be newly defined, but the rights regarding the wholesale market, transmission, distribution, metering, and retail market are still largely applicable. For the latter segments it needs to be defined where the ownership and decision rights need to be adjusted. A public supervisory body needs to be delegated that conducts the permitting process and the monitoring and control of the safe operation of the production facilities.

A competitive hydrogen market is unlikely to emerge on the short-term due to the lack of supply and demand. Shippers need to be licensed to trade hydrogen and the ACM needs to become active in the monitoring and control of the hydrogen provision. The latter would imply that the Gas Act and the energy codes need to be reformulated regarding the specific market rules and regulations regarding to address hydrogen. The market design of the gas sector needs to address the trade in hydrogen, and it needs to be determined what rules will structure the hydrogen transactions.

Clear gas qualities need to be allocated to the existing public gas grids that need to be monitored and controlled by the concerned system operators. The forecasts of the hydrogen supply are that hydrogen will not be able to replace the total gas demand on the short-term. With the integration of hydrogen gas, it will hence be difficult to provide end-users with non-discriminatory access to a hydrogen grid. Only parts of the natural gas transmission and distribution grids can be transformed to hydrogen since there will not be enough supply and since other alternatives to natural gas will emerge. Consumers will be bounded to their physical locations in terms of the possibilities to be connected to a hydrogen grid. The choices of the end-users to utilize hydrogen are hence not free anymore. In a future comprehensive hydrogen system with enough supply and demand it will be easier to address the non-discriminatory access to the public grids.

The property rights regime of the natural gas infrastructure clearly defines the ownership and decision rights regarding market activities. This regime allocates the economic risks of the gas provision to the various entities. The hydrogen laws and regulations and thus the property rights regime is currently

undefined. There is uncertainty about how the costs and benefits of the hydrogen infrastructure will be allocated. This uncertainty in the property rights regime results in a negative investment climate. The government should define a level playing field for hydrogen that addresses the immaturity of the system.

### **5.2.6 Industry standards**

Industry standards regarding the products, services, and assets of a hydrogen infrastructure are necessary. Gas quality standards need to be defined and stated in the regulations to determine the specific standards for the asset characteristics. The operational activities should be adjusted to these new standards. Operational requirements and limits for metering and system management activities need to be stated in the energy codes. The different gas qualities will require other safety limits to be defined. The certification processes need to match the changing requirements (i.e. changing requirements for the installation and operation of assets). All these new standards need to be formulated on a European and national level. The current industry standards are largely compatible with the provision of hydrogen but will need to be adjusted where they are not.

### **5.2.7 Contractual arrangements and modes of organization**

The transactions of the natural gas volumes are currently conducted within the framework of the natural gas wholesale market. It will be difficult to determine the price of hydrogen since no adequate price-signals are given by the hydrogen market. From a viewpoint of fair prices and supply side protection, the regulation on the hydrogen prices will become more important. A clear market design is needed to accommodate the uncertainties regarding the prices and hence the investments in hydrogen assets. Such a design cannot be made in isolation from the existing energy and feedstock markets.

The capacity of the potential hydrogen provision is dependent on the transformation of the Dutch gas grid. It is unsure whether the infrastructure will be transformed and where it will be transformed. Municipalities, DSOs, the TSO, potential producers, storage operators, and suppliers need to collaborate to transform the existing natural gas grids into hydrogen grids. Currently the level playing field for hydrogen is undefined and hence unsure. Direction of the government can help these latter parties to collaborate and determine the mutual operational and economic interdependencies. Due to the uncertainty in the level playing field, investments are unlikely to occur on a large-scale. Transport capacity, production capacity, and storage capacity will hence be bounded to long-term contracts instead of more flexible modes of organization. Hydrogen gas could be provided from a vertically integrated monopoly to overcome the uncertainty of a level playing field. Laws and regulations will hence have to change, and the consumer sovereignty cannot be safeguarded anymore.

Transportation tariffs will be unavoidably higher than the current tariffs for natural gas due to the higher capital and operational costs. In the current gas system, the capital and operational costs are socialized over all the gas connections. The latter will make it hard to compete with other heating alternatives since the existing systems do not have these intensive capital costs. Moreover, these systems are not designed to be carbon free. To bridge the gap between these alternatives the costs of the hydrogen system need to be socialized differently. The costs can for example be socialized at the supply side of gas or through the electricity consumers in the built environment. The latter would imply that the electricity and gas distribution activities will become integrated. The focus will shift from two systems to one system that provides energy in a cost-efficient way from a total system perspective. The district heating infrastructure can be added when it is extensive enough to have the similar characteristics as the electricity and gas distribution grids in terms of the provision of energy. The interaction between the gas, electricity, and heat distribution grids can potentially be provided as a conversion service by the

system operators (i.e. in a similar fashion like the natural gas blending services). The latter requires a well-functioning market to transact energy in. There will be no need for the transaction of conversion capacity if specific energy carriers are transacted.

The production capacity adequacy of hydrogen needs to be organized differently since it does not directly include the exploitation of natural resources. Capacity mechanisms could be necessary for the long-term production capacity adequacy. The modes of organization regarding the hydrogen production capacity adequacy can become much like the modes of organization in the electricity production. The main difference is that the hydrogen transactions will not provide a market-based price signal for investment. The latter requires more government intervention to organize the long-term production capacity adequacy.

Hydrogen storage capacity will become more important due to the loss of the flexible production of natural gas. For the long-term storage capacity, it still might be economically viable to store natural gas. The supply of hydrogen will hence be dependent on the steam methane reformation capacity. In such a situation, the steam methane reformation capacity needs to be adequate and extensive. When the hydrogen production system becomes more dependent on the production of green hydrogen, hydrogen storage will be needed to store the hydrogen for both the seasonal fluctuations as for the eventualities. To organize the emergence of enough storage capacity, hydrogen prices and the certainty of supply are important for storage operators. The latter requires, in analogy with the hydrogen production facilities, certainty in prices and demand since market signals are not present. This implies that the storage tariffs need to be regulated and the hydrogen prices need to include the costs of storage.

The hydrogen transport adequacy of the public grids will be dependent on the way in which the public service obligations of the system operators will still be active. Currently, system operators have a connection obligation but not a transport obligation. The latter means that all producers and consumers need to be connected to the gas grids, but producers can be shut down if the capacity of the grid does not allow the wanted transport service. It needs to be determined whether this system should be applicable to hydrogen connections too. Considering the problem of the absence of supply and demand, the current system of connection obligations can generate uncertainty in terms of the transport capacity. Especially, when the local supply exceeds the demand for gas or transport capacity. The hydrogen provision hence needs to be coordinated in such a way that investments in production and end-use capacity can be safeguarded.

### **5.2.8 Degree of horizontal and vertical integration**

The integration of hydrogen will require an intensive coordination role for the system operators in terms of the emergence of entry and exit points. Transactions need to be coordinated in the absence of a well-functioning market. From this perspective it could be desirable that system operators can participate in more activities regarding the provision of hydrogen. System operators can for example start with the conversion of parts of their grids and hence facilitating the needed production and storage capacity, and the installment of the necessary end-use equipment. Within the current laws and regulations, system operators are only allowed to participate in these activities in an experimental setting. System operators could for example play a role in tenders to realize the production facilities. These tenders could also be organized broader in which a system operator tenders all the hydrogen related activities around a specific part of the grid.

As described in the previous section it could be desirable to integrate the various distribution activities of energy in the built environment. System operators are hence able to strive for total system efficiencies. Due to the nature of the conversion of hydrogen, it needs to be determined if system operators can be allowed to converge the various energy distribution systems. They will hence be automatically involved in hydrogen conversion activities (i.e. production activities) when electricity is converted to hydrogen and delivered to the end-user. The various energy carriers that can be used to produce hydrogen imply the hydrogen sector to be intertwined with suppliers of biomass, electricity, natural gas, methanol, ethanol, coal, et cetera. It needs to be determined whether it is desirable for hydrogen producers to integrate the various steps in the supply chains. When the hydrogen system is more mature it could be desirable to unbundle and liberalize the various activities again and allow for more competition in the energy system.

### **5.2.9 Principal-agent and opportunistic behavior safeguards**

The supervision of ACM over the hydrogen sector needs hydrogen energy codes or adjusted gas codes. ACM needs to be involved in the issuing of permits to retail suppliers. Hydrogen underground storage activities are not yet part of the laws and regulations that the SodM supervises. Moreover, the Mining Act does not allow for the storage of hydrogen. A new supervisory task is introduced by the new production segment of hydrogen. Rules need to be established that are applicable for the various production technologies at various locations and scales. Laws and regulations need to be formulated and a supervisory body needs to exist that monitors and controls them. It needs to be determined how hydrogen production permits will be issued. Currently the siting of hydrogen production plants is not specifically subject to national regulations. The siting is included in the acts about environmental law and the development plans of the provinces and the municipalities. It needs to be determined whether a national permit issuing procedure will be included, and which supervisory body is going to conduct the permitting process.

### 5.3 Challenges and complementarity within the system design and the economic institutions

The changes described in section 5.1 and section 5.2 result in a variety of challenges of the integration of hydrogen regarding the specific layers of the comprehensive design framework. The design issues in the system design cause design issues in the economic institutions and vice versa. This section will elaborate on the challenges that are caused by the integration of hydrogen. First the challenges in the system design will be linked to the design issues in the economic institutions and then the challenges in the economic institutions will be linked to the design issues in the system design.

#### 5.3.1 Challenges in the system design linked to the economic institutions

The design issues in every system design layer call for design choices in the various layers of economic institutions. Table 12 presents the challenges in the system design of the access layer on the left and hence couples the important choices that need to be made in the economic institutions to the right (i.e. the various layers of economic institutions). The numbers in column one in between brackets illustrate the hydrogen infrastructure options. Some challenges are hence specific for a particular hydrogen infrastructure option. Table 13 presents the challenges of the responsibilities layer of the system design coupled to the important choices that need to be made in the various layers of the economic institutions. Table 14 presents the challenges for the coordination layer of the system design and the important choices that need to be made in the economic institutions.

Challenges in system design	Related design challenges in the three layers of the economic institutions
<p><u>Access</u></p> <ul style="list-style-type: none"> <li>Gas production becomes dependent on a variety of energy sources and hence on the interaction with other systems and the resource availability of these systems. [1+2]</li> <li>More gas producers can enter the production segment due to the less stringent entry barriers compared to the situation with the natural gas fields. [1+2]</li> </ul>	<p><u>Access</u></p> <ul style="list-style-type: none"> <li>Determine the degree of competition in between the hydrogen production technologies and hence in between the various systems of energy inputs.</li> <li>Determine the degree of competition that is desirable between the storage facilities.</li> <li>Determine which technologies should make up the production and storage segment of hydrogen.</li> <li>Determine whether the various distribution grids need to be converged and compete on the level of energy content.</li> </ul>

Challenges in system design	Related design challenges in the three layers of the economic institutions
<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>• The buffer capacity of a hydrogen system decreases and needs to be organized differently compared to natural gas. [1+2]</li> <li>• Micro-grids can change the way in which the gas provision is organized in the gas grid. [1+2]</li> <li>• The possibility of converting electricity into heat and gas in various locations of the energy grids (i.e. electricity, gas, and district heating) fundamentally changes the interaction between the systems. [1+2]</li> <li>• The production of blue hydrogen introduces dependencies on fossil fuels and CCS infrastructure. [1+2]</li> <li>• The production of green hydrogen creates the dependency on renewable electricity surplus and biomass. [1+2]</li> <li>• The decentralized production of hydrogen fundamentally changes the system architecture of the gas grid due to the shift in supply towards the distribution grids. [2]</li> <li>• The decentralized possibility of storage fundamentally changes the system architecture of the gas grid due to the shift in supply and demand to the distribution grids. [2]</li> <li>• The production of blue hydrogen cannot be conducted on a small-scale. [2]</li> </ul>	<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• Determine the access conditions regarding every hydrogen production and storage technology on every specific scale.</li> <li>• Determine which hydrogen production and storage activities can be publicly or privately conducted.</li> <li>• Determine whether the emergence of micro-grids should be subject to the Gas Act.</li> <li>• Determine gas quality and gas flow rate standards for every specific part of the gas grid.</li> <li>• Determine the conversion (i.e. electricity to gas and heat) possibilities of system operators in the Gas Act, Electricity Act, and Heat Act.</li> <li>• The Gas Act and energy codes need to be adjusted for new characteristics of the gas flow and gas quality.</li> </ul> <p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>• Determine how energy input for hydrogen can be contracted.</li> <li>• Determine how energy content and grid connections will be transacted among gas suppliers and the end-users in the built environment.</li> <li>• Determine how production and storage capacity adequacy can be safeguarded under fair prices and the dependency of the various energy inputs.</li> </ul>

Table 12: System design challenges in the access layer linked to their consistency challenges in three layers of economic institutions



Challenges in system design	Related design challenges in the three layers of the economic institutions
<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• The network topology of the hydrogen transmission and distribution grids is strongly dependent on where supply and demand will emerge. [1+2]</li> <li>• The possibilities of CCS infrastructure constraints the design of the network topology. [1+2]</li> <li>• Determine the share of the supply that will be dependent on hydrogen imports. [1+2]</li> <li>• Determine the share of energy input that will be dependent on imports of biomass and fossil fuels. [1+2]</li> <li>• Siting enough wind and solar energy capacity in combination with hydrogen production facilities will be a challenge. [1+2]</li> <li>• The security and flexibility of supply in a hydrogen system will decrease because of smaller production and storage capacities and higher import dependencies. [1+2]</li> <li>• Transport capacity of the grids will need higher gas flow rates to compensate for the lower volumetric energy density of hydrogen gas. [1+2]</li> <li>• Determine whether the entry and exit points of the gas grid are adequate and hence determine whether new entry and exit points are possible. [1+2]</li> <li>• Determine the extent to which the distribution grids can accommodate decentralized injected gas. [2]</li> </ul>	<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>• Determine whether hydrogen gas will compete with natural gas.</li> <li>• Determine how the various production technologies (centralized and decentralized) will compete in what markets.</li> <li>• Determine the degree of import dependency from other countries.</li> <li>• Determine the degree of competition in between the hydrogen production technologies and hence in between the various systems of energy inputs.</li> <li>• Determine whether system operators can participate in commercial activities and how.</li> </ul> <p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• Determine the mechanisms of the connection and transportation obligations of the system operators in the transmission and distribution grid regarding hydrogen connections.</li> <li>• Determine gas quality and gas flow rate standards for every specific part of the gas grid and adjust Gas Act and energy codes.</li> <li>• Determine the access conditions regarding every hydrogen production and storage technology on every specific scale.</li> <li>• Determine the delineation of hydrogen production and CCS activities.</li> <li>• Determine which parties (i.e. public or private) can participate in the import of hydrogen and its energy inputs.</li> <li>• The Mining Act needs to be adjusted to allow for the underground storage of hydrogen.</li> <li>• Production capacity adequacy mechanisms need to emerge (i.e. especially on the short-term).</li> <li>• Security of demand needs to be safeguarded (i.e. especially on the short-term).</li> <li>• Determine and state new ownership and decision rights regarding hydrogen production facilities and the interaction with the public grids.</li> </ul>

Challenges in system design	Related design challenges in the three layers of the economic institutions
<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>Determine where new entry points can emerge for the decentralized gas producers. [2]</li> </ul>	<p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>Determine how contractual arrangements about the supply and demand (i.e. supply and demand of transport services, storage services, and energy content) between hydrogen producers, storage operators, system operators, retail suppliers, and consumers will be established.</li> <li>Determine the supervisory body regarding the hydrogen production segment.</li> <li>Determine how security on investments can be safeguarded regarding the base and peak load of gas and the development of the demand-side.</li> </ul>

Table 13: System design challenges in the responsibilities layer linked to their consistency challenges in three layers of economic institutions

Challenges in system design	Related design challenges in the three layers of the economic institutions
<p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>Coordination higher gas flow rates and lower supply and demand of hydrogen gas. [1+2]</li> <li>Coordination other gas characteristics (i.e. requirements for gas quality, temperature, and gas flow rate). [1+2]</li> <li>Coordination of decentralized production and storage (i.e. supply on the level of the distribution grids). [2]</li> </ul>	<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>Determine how the local supply of gas is transacted.</li> </ul> <p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>Determine the mechanisms of the connection and transportation obligations of the system operators in the transmission and distribution grid regarding hydrogen connections.</li> <li>Determine whether system operators can own and operate conversion and storage assets.</li> <li>Determine which balancing regime will be used in the transmission and distribution grids.</li> <li>Industry standards need to be formulated regarding the design, installment, and operation of all the assets.</li> <li>Determine gas quality and gas flow rate standards for every specific part of the gas grid and adjust Gas Act and energy codes.</li> </ul>

Challenges in system design	Related design challenges in the three layers of the economic institutions
<u>Coordination</u>	<u>Coordination</u> <ul style="list-style-type: none"> <li>• Determine how suppliers can be shut down or scaled up for the purpose of balancing the grid.</li> <li>• Determine the supervisory body regarding the hydrogen production segment.</li> </ul>

Table 14: System design challenges in the coordination layer linked to their consistency challenges in three layers of economic institutions

### 5.3.2 Challenges in the economic institutions linked to the system design

The challenges in every layer of economic institutions on the other hand, call for design choices in the various layers of system design variables. Table 15 presents the challenges in the economic institutions of the access layer on the left and hence couples the important choices that need to be made in the system design variables to the right (i.e. the various layers of system design). The numbers in column one in between brackets illustrate the hydrogen infrastructure options. Some challenges are hence specific for a particular hydrogen infrastructure option. Table 16 presents the challenges of the responsibilities layer of the economic institutions coupled to the important choices that need to be made in the various layers of the system design variables. Table 17 presents the challenges for the coordination layer of the economic institutions and the important choices that need to be made in the system design variables.

Design challenges in the economic institutions	Related design challenges in the three layers of system design
<u>Access</u> <ul style="list-style-type: none"> <li>• Hydrogen can be considered a conversion process or a production process. [1+2]</li> <li>• No market for hydrogen will emerge on the short-term [1+2]</li> <li>• Determine whether the energy provision to the built environment should be integrated in one system integrated energy system. [1+2]</li> <li>• Determine the degree to which consumers in the built environment can choose their energy carrier. [1+2]</li> </ul>	<u>Access</u> <ul style="list-style-type: none"> <li>• The system architecture in the short-term is likely to be based on centralized hubs of supply.</li> <li>• Determine which interactions with other systems (i.e. electricity, district heating, CCS, biomass, natural gas) are possible and desirable.</li> <li>• Determine where the decentralized supply will be injected (i.e. which specific transmission or distribution grid).</li> <li>• More interaction between the gas grids and various producers will emerge because of the less stringent entry barriers.</li> </ul>

Design challenges in the economic institutions	Related design challenges in the three layers of system design
<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>• The gas production segment can become more liberalized due to the less stringent entry barriers. [1+2]</li> <li>• Dependencies and interrelations of the gas infrastructure with the systems of energy input, CCS, hydrogen storage, and natural gas storage need to be defined and regulated. [1+2]</li> <li>• Needs to be determined whether system operators can be active in any commercial activities and how. [1+2]</li> <li>• Determine how the supply of decentralized hydrogen will be transacted. [2]</li> </ul>	<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• The adequacy of the network topology design will be dependent on the number of producers and the degree of centralized and decentralized supply that emerges.</li> <li>• The design of the distribution grid network topologies will be dependent on the degree to which hydrogen is adopted by the end-users in the built environment.</li> <li>• Convergence of distribution grids (i.e. electricity, district heating, and gas) enhances system efficiencies in terms of costs and capacity adequacy and is dependent on the allowance of system operators to be active in the conversion of electricity to gas and heat.</li> <li>• High degree of distribution level gas injection will result in bilateral grids. New pipelines need to be constructed and boosters need to be installed.</li> </ul> <p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>• The higher the degree of variety in private hydrogen producers the more intensive the coordination mechanisms need to be regarding the injection of gas (i.e. monitoring and control of volume and quality) and the gas flow (bidirectional flow and fluctuating supply and demand patterns).</li> <li>• The supply of gas can shift to relatively larger number of gas producers.</li> <li>• The gas grid will need to interact with a variety of other systems which will make the operational coordination in terms of supply fluctuations more complex.</li> <li>• Balancing of the transmission and distribution grid becomes more difficult due to the less flexible supply and other supply patterns.</li> </ul>

Table 15: Economic-institutional design challenges in the access layer linked to their consistency challenges in three layers of system design variables

Challenges in formulation economic institutions	Issues of complementarity in system design
<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• Access rules regarding the hydrogen production and storage technologies on the various scales are undefined regarding the interaction of the public gas grids. [1+2]</li> </ul>	<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>• Strict access regulations will result in relatively small number of large producers on tactical locations (i.e. regarding system efficiency) and require less adjustments in the system architecture.</li> </ul>

Challenges in formulation economic institutions	Issues of complementarity in system design
<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• Consumer sovereignty at the end-users is hard to be established from a total system efficiency perspective. [1+2]</li> <li>• Blue Hydrogen will be unavoidably more expensive on the short-term than its substitutes due to the costs of CCS (i.e. the price for CO<sub>2</sub> sequestration). [1+2]</li> <li>• The energy input of green hydrogen from wind and solar is cheaper than fossil fuels due to the low marginal costs of these technologies. [1+2]</li> <li>• Electricity from RES will always be cheaper to utilize directly than to convert to hydrogen due to the extra conversion step. This effect can be compensated by the more efficient transportation and storage of gas over long distances and large time-spans. [1+2]</li> <li>• Energy tariff structures cannot be seen in isolation in terms of socialization possibilities and green energy. [1+2]</li> <li>• Undefined ownership and decision rights (i.e. level playing field) result in uncertainty and hence in high-investment risks. [1+2]</li> <li>• Ownership and decision rights of system operators change from the provision of natural gas to the provision of hydrogen gas and from the blending activities (i.e. natural gas conversion activities) possible to the hydrogen conversion activities (i.e. from electricity and/or natural gas). [1+2]</li> <li>• The Gas Act and energy codes need to be reformulated for the provision of hydrogen gas. [1+2]</li> </ul>	<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>• Gentle access regulation allows for the emergence of a relatively larger number of smaller producers at less tactical locations and requires the system architecture to fundamentally change. The supply shifts from current entry points to a variety of entry points at various locations.</li> <li>• Consumer sovereignty in terms of energy carrier requires a complex and costly system architecture.</li> <li>• The choice in the interaction between the energy tariff structure in terms of greenhouse gas emissions and socialization determine the dependencies and interactions between the various energy systems. A universal energy and CO<sub>2</sub> market will generally result in an integrated energy system. Isolated tariff structures generally in more isolated systems.</li> <li>• The definition of ownership and decision rights regarding the various assets of the system will determine which technologies can emerge where. Moreover, it will determine how much state infringement is possible and hence how controllable the design of the system architecture will be.</li> <li>• When system operators can merge their distribution activities (i.e. electricity and gas) the interaction between those systems changes.</li> </ul> <p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• The adequacy of the network topology design will be dependent on the number of producers and the degree of centralized and decentralized supply that emerges.</li> <li>• High degree of distribution level gas injection will result in bilateral grids. New pipelines need to be constructed and boosters need to be installed.</li> <li>• The network topology will be dependent on the degree to which energy tariffs will be merged.</li> <li>• The network topology will be dependent on the allowance (i.e. allocation of ownership and decision rights) of producers and storage operators to emerge at various locations in the grid.</li> </ul>

Challenges in formulation economic institutions	Issues of complementarity in system design
<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>The market rules need to be reformulated when hydrogen will be transacted, especially considering the absence of enough supply and demand on the short term and the changing character of the transactions. [1+2]</li> </ul>	<p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>The higher the degree of consumer sovereignty the more complex and cost intensive the operational coordination of the gas grid gets.</li> <li>The higher the degree of variety in private hydrogen producers the more intensive the coordination mechanisms need to be regarding the injection of gas (i.e. monitoring and control of volume and quality) and the gas flow (bidirectional flow and fluctuating supply and demand patterns).</li> <li>The supply of gas can shift to relatively larger number of gas producers.</li> <li>The gas grid will need to interact with a variety of other systems which will make the operational coordination in terms of supply fluctuations more complex.</li> <li>Balancing of the transmission and distribution grid becomes more difficult due to the less flexible supply and other supply patterns.</li> <li>Coordination mechanisms will be dependent on the degree to which energy tariffs will be merged. Coordination between the systems will become much more important when the energy tariffs are merged.</li> </ul>

Table 16: Economic-institutional design challenges in the responsibilities layer linked to their consistency challenges in three layers of system design variables

Challenges in formulation economic institutions	Issues of complementarity in system design
<p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>No price-signals due to the absence of a well-functioning market on the short term. [1+2]</li> <li>Need for long-term bilateral contracts. [1+2]</li> <li>Consumer sovereignty infringement by local energy strategies. [1+2]</li> </ul>	<p><b><u>Access</u></b></p> <ul style="list-style-type: none"> <li>The absence of a well-functioning market will make the design of the system architecture dependent on the emerging bilateral contracts.</li> <li>A connection obligation will result in a less controllable interaction between the public grids and the gas production segment.</li> </ul>

Challenges in formulation economic institutions	Issues of complementarity in system design
<p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>• Need for capacity adequacy mechanism in more open gas production segment. [1+2]</li> <li>• The need for more intensive role of the system operators in emergence of hydrogen systems. [1+2]</li> <li>• The need for a supervisory body regarding the hydrogen production segment. [1+2]</li> <li>• The limits of connection obligation under a large share of decentral available supply. [2]</li> </ul>	<p><b><u>Responsibilities</u></b></p> <ul style="list-style-type: none"> <li>• The absence of a price-signal for investments and hence the needs for bilateral contracts will require supply and demand to emerge at specific cost-efficient locations.</li> <li>• The energy strategies will determine to a large extent which part of the gas distribution grids will be used for the provision of hydrogen.</li> <li>• Production capacity adequacy will be much more dependent on long-term contracts in both the supply as demand side.</li> <li>• A connection obligation will hamper the possibility for the system operators to strive for total system efficiency in terms of costs and energetic performances.</li> </ul> <hr/> <p><b><u>Coordination</u></b></p> <ul style="list-style-type: none"> <li>• The energy strategies require an intensive coordinating role of the DSOs due to the constraints of the electricity and gas grids.</li> <li>• The balancing regime will be much more dependent on adequate capacity mechanisms.</li> <li>• A large share of decentralized supply availability will require more complex and costly distribution networks to emerge.</li> </ul>

Table 17: Economic-institutional design challenges in the coordination layer linked to their consistency challenges in three layers of system design variables

## **5.4 Main challenges in system design**

The main challenges of the integration of hydrogen can be categorized in system design challenges and challenges in the design of the economic institutions of the gas infrastructure. The system design challenges interact with the challenges in the design of the economic institutions and vice versa. The main challenges in the system design are elaborated on in this section and the main challenges in the design of the economic institutions in the next. Besides to the latter categorization, the challenges are either categorized as challenges for both hydrogen infrastructure options (i.e. option 1 and option 2) or as challenges for the decentralized hydrogen infrastructure option (i.e. option 2). The first seven challenges are applicable to both options and the latter 2 arise because of the large-scale integration of local supply.

### **5.4.1 Interaction with the systems of energy input to produce hydrogen**

The hydrogen production segment will be dependent on the availability of various energy carriers (i.e. such as natural gas, biomass, renewable electricity, and electricity) including their own cost and tariff structures, their own supply patterns, and their own acceptance criteria regarding their impact on society and the environment. The supply of the energy carriers is dependent on the specific supply chains that differ in scale and outreach. These distinctive systems need to be coupled to the production segment of hydrogen. High quantities of energy input (i.e. energy carriers) need to be available at various locations in the gas infrastructure. These locations are dependent on the possibilities of the storage and transportation of the energy carriers and the applicable access and tariff regulations. The locations of the hydrogen production and storage facilities are hence dependent the dynamics of the various energy input systems and to the economic institutions active in these systems.

### **5.4.2 Interaction with natural gas infrastructure**

The natural gas infrastructure is a comprehensive infrastructure system that allows for the injection, storage, and distribution of natural gas. The gas infrastructure is hence designed to be operational under specific gas qualities, specific pressure levels, and specific temperatures. The design of the gas infrastructure needs to be adjusted to the properties of hydrogen gas. The transformation of the gas infrastructure hence includes a path-dependency of the specific gas characteristics that are chosen for a specific part of the gas system. When hydrogen will be injected, stored, and distributed in a specific part of the gas infrastructure, natural gas cannot be utilized anymore. With the emergence of steam methane reformation to produce hydrogen, natural gas still needs to be available at the locations where it is converted into hydrogen. The latter implies that a part of the natural gas infrastructure needs to exist alongside a hydrogen gas infrastructure when blue hydrogen is produced through steam methane reformation.

### **5.4.3 Interaction with CCS infrastructure**

The production of blue hydrogen (i.e. including the sequestration of CO<sub>2</sub>) will be a dominant production method on the short-term due to the unavailability of adequate energy inputs from renewable electricity and biomass. The latter implies that CCS infrastructure needs to emerge and need to be integrated in the blue hydrogen production processes. The CO<sub>2</sub> can be transported by existing or by newly constructed pipeline networks. The storage of CO<sub>2</sub> can be conducted in already connected or newly developed storage facilities. The transportation and storage of CO<sub>2</sub> will imply the same kind of path-dependency as described between the hydrogen and natural gas regarding the use of the existing gas infrastructure. The construction of new CCS infrastructure can be costly.



#### **5.4.4 The emergence of hydrogen supply and demand**

The emergence of hydrogen supply will be dependent on the hydrogen production capacity that will be installed and the possibilities for hydrogen imports. The realization of the hydrogen supply infrastructure will be dependent on clarity regarding the hydrogen production technologies that can emerge, under which conditions, and at what locations in the system. Moreover, clarity needs to exist about the emergence of enough hydrogen supply in the built environment for longer periods. The design of the hydrogen gas infrastructure will hence be dependent on the type of supply and demand that will emerge at specific locations in the system. A higher number of and more variety in hydrogen suppliers will require a more operational and cost intensive design of the gas infrastructure than with a relatively small number of uniform suppliers.

#### **5.4.5 Organization of hydrogen buffer capacity**

The organization of buffer capacity in a hydrogen gas infrastructure will fundamentally change compared to the existing organization of buffer capacity. The natural gas buffer capacity is enormous in terms of volume and flexibility. The natural gas production capacity and gas reserves, in both storage facilities and natural gas fields, are enormous. Especially the extraordinary large Groningen gas field contributes to the large flexibility in supply and the enormous gas reserves. The mature natural gas market also contributes to the availability in supply from natural gas imports. The buffer capacity of hydrogen gas will be predominantly dependent on the production and storage capacity of hydrogen gas. These latter two capacities will be unavoidably less comprehensive as the current natural gas storage and production capacities, especially on the short-term. The green hydrogen supply will be able to provide a relatively small part of the hydrogen buffer capacity on the short-term. The latter is, next to the inexistence of renewable electricity capacity, caused by the relatively volatile demand of renewable energy. Moreover, green hydrogen will largely be produced from renewable electricity surplus, which is not likely to emerge in enormous quantities on the short-term. The availability of biomass is also a constraining factor for the organization of green hydrogen buffer capacity. The buffer capacity of green hydrogen will hence be largely dependent on the storage of green hydrogen and the imports of green hydrogen from area with higher renewable energy yields. Blue hydrogen, however, includes more possibilities to organize a flexible and adequate buffer capacity. These possibilities are based on the storability of the energy input of the blue hydrogen production processes. The blue hydrogen production capacity is hence the dominant constraining factor in the organization of buffer capacity. When adequate blue hydrogen production capacities are available, a part of the buffer capacity can be organized outside of the hydrogen gas infrastructure (i.e. stored in other energy carriers than hydrogen).

#### **5.4.6 Interaction with electricity grid**

The existing gas and electricity grids are designed to match supply and demand of the concerned energy carrier. With the integration of hydrogen in the gas infrastructure, it becomes possible to convert electricity into gas through the electrolysis of water. The interaction between the electricity and gas grids will hence no longer be one-sided. The interaction between both grids will fundamentally change. The possibility of converting electricity into gas allows for the storage and transportation of renewable energy sources in the form of gas. The possibility of generating electricity from gas through local fuel cells provides the possibility to provide the electricity demand with gas. Moreover, the gas infrastructure can provide the electricity sector with the needed buffer capacity of the volatile supply of green electricity.

#### **5.4.7 Interaction with district heating grids**

The hydrogen production processes generate heat. The same applies to the conversion of gas into electricity from non-renewable sources including biomass. The heat demand of the built environment can be partly provided by the excess heat of the hydrogen and electricity production processes. District heating networks are necessary to connect the heat supply with the built environment. The construction of district heating networks is costly and requires the possibility to construct pipeline networks from the suppliers and consumers. Other than electricity and gas, district heating networks are not a convenient way of transporting energy over long distances due to the relatively higher energy losses. The tactical siting of the hydrogen production facilities can hence allow district heating to emerge and reduce the demand for hydrogen in the built environment. The heat supply of the district heating networks can also be complemented by the combustion of hydrogen. The latter provides the grids with a larger flexibility in terms of supply. Existing district heating grids based on the combustion of natural gas can be converted to grids based on the combustion of hydrogen.

#### **5.4.8 Interaction between the gas transmission and distribution grids**

The interaction between the natural gas transmission and distribution grids is largely determined by the centralized supply of gas that is transported in a top-down fashion from the high-pressure grids to the lower pressure grids. The shift from a centralized gas supply to a decentralized gas supply hence changes the interaction between the transmission and distribution grids. The locally produced gas needs to be injected in the distribution grids. The entry of gas in the distribution grids will no longer be dominantly based on the connection with the transmission grids. New entry points will emerge in the distribution grids. The injection of gas in the distribution grids will hence also be injected locally (i.e. as with the developments of the decentralized injection of green gas). The supply of gas from the transmission grids to the distribution grids will hence decrease. Moreover, when the local gas supply exceeds the local gas demand, the distribution grid will become saturated due to the lack of buffer capacity. Demand for the gas surplus can still exist in other areas that are not directly connected. The distribution grids need to be adjusted to facilitate the transaction of the gas surplus to other areas of demand. When the demand for gas is situated in the transmission grid, a bidirectional gas flow is necessary to transport the gas from the distribution to the transmission grids and in the transmission grids. The bidirectional flow refers to the gas flow against the pressure drop of the network facilitated by boosters. When the demand for gas is situated nearby the local supply, new pipeline networks can be constructed. A distribution grid with a large share of local supply will become more costly and operational intensive.

#### **5.4.9 Possibilities of local gas supply**

The decentralized production of green gas is currently dependent on the local availability of biomass. The decentralized production of hydrogen will also be dependent on other energy carriers next to biomass. The local availability of natural gas can hence be a problem due to the transformation of the natural gas grids into hydrogen distribution grids. The local availability of electricity is rather comprehensive due to the national electricity grid. The share of locally available renewable electricity is however marginal. Local renewable electricity producers can produce hydrogen from their renewable electricity surplus. The siting of the production facilities nearby the areas of demand can be problematic due to inclusion of CCS infrastructure and the siting of the wind mills and solar panels. The gas supply will also be dependent on large production facilities and hence on the transmission of hydrogen over longer distances. The type of local production technologies that can emerge are dependent on the availability of the energy input, the characteristics of production technology, and the scale of the production technology.

## **5.5 Economic institutional design challenges**

The main challenges of the integration of hydrogen to the design of the economic institutions are elaborated on in this section. The first six challenges are applicable to both hydrogen option 1 and hydrogen option 2. The latter two challenges are only applicable when a large-share of local supply occurs in the system.

### **5.5.1 Development of a hydrogen market on the short-term**

Fundamental in the development of a well-functioning gas market is the presence of adequate amounts of supply and demand. The public natural gas grids are openly accessible to enhance the market functioning in the system. The transformation to a hydrogen system requires large up-front investments in specific production, transportation, storage, and end-use assets. Relationships between the various actors in the supply chain of hydrogen gas hence become more important to earn the investments back. The natural gas wholesale market partly consists of bilateral gas transactions and spot market gas transactions. The natural gas transactions in the wholesale market are largely based on short term transactions in the spot market. With the asset specificity and the lack of supply and demand (i.e. the absence of a well-functioning spot market), hydrogen transactions are likely to be based on bilateral contracts for longer durations. The latter fundamentally changes how gas is transacted and how the storage and transport services are transacted. Transactions will become more static over time and will include less possibilities for alternatives and no adequate price signal will be provided by the market. To prevent opportunism and unfair prices from occurring, tariffs should be regulated more strictly than in a well-functioning market. The ACM hence gets a more intensive role in determining the price restrictions of the transactions in the hydrogen system.

### **5.5.2 Interaction between the various markets connected to the hydrogen supply and demand**

The supply of hydrogen will become dependent on the availability of electricity, biomass, natural gas, and other fossil fuels and feedstocks. The price of hydrogen will hence be dependent on the markets in which these energy carriers are transacted. The price of hydrogen and the possibilities for the regulation of the price are therewith dependent on the functioning of various market and the interactions between these markets. The mutual interdependencies are strengthened by the joint cost structure nature the hydrogen production from steam reformation, and gasification and pyrolysis. At the demand side in the built environment, hydrogen can be substituted by electricity and heat. Important is that these substitutes include the same requirements regarding the CO<sub>2</sub> emissions of the production of heat, electricity, and gas. Without the same standards or taxation principles applicable to the production of the various energy carriers, unfair competition will emerge. This effect will be strengthened by the more capital cost and operational cost intensive character of the emerging hydrogen production segment compared to the electricity and district heating systems that are already in place.

### **5.5.3 Interaction between the electricity, gas, and heat grids**

Heat, electricity, and hydrogen are all energy carriers that are based on the same primary energy sources. The conversion of these primary energy sources into electricity, hydrogen, or heat depends largely how the energy will be distributed, stored, and used in terms of its application, costs, environmental impact, and energy efficiency. Heat is predominantly generated by the combustion of natural gas, electricity by the combustion of fossil fuels and hydrogen will be predominantly dependent on fossil fuels on the short-term. Renewable energy sources need to replace the use of fossil fuels and will hence determine which energy carriers will be convenient in terms of its application, costs, environmental impact, and energy efficiency. The gas, district heating, and electricity infrastructures are currently considered as

separate systems with a relatively closed architecture in terms of the energy carrier that is distributed from the transmission to the distribution grids. The provision of gas, electricity, and heat include their own Gas Act, Electricity Act, and Heat Act. The energy codes are also separated in distinctive codes for natural gas and electricity. This view on the provision of energy does not actively include the total system efficiencies and externalities of an integrated energy system. Efficiencies in terms of costs, availability, and energy performance are hence largely considered within the boundaries of a single system perspective. Investment in the electricity grids can for example not be earned back in the gas grids due to the existing tariff structures. External costs, such as the costs of CO<sub>2</sub> emissions, are hard to allocate across the specific energy systems. The latter effect is strengthened by the intranational character of the including fossil fuel markets. An integrated energy system viewpoint can contribute to the realization of a total system efficiencies. For the energy provision in the built environment this would imply that DSOs can also approve or refuse a grid connection based on a total system efficiency perspective. Gas, district heating, and electricity grids will hence emerge based on an efficient provision of energy for a specific area and application. The latter fundamentally changes the way in which energy is currently provided. The availability of electricity and gas are currently separate public services.

#### **5.5.4 The role of the system operators**

System operators are not allowed to participate in any activities not related to the transport and conversion of natural gas within the strictly defined rules and operational limits. The latter rules are stated in the Gas Act and more specifically in the energy codes. When system operators need to become active in the provision of hydrogen, current rules need to be renewed regarding the operational requirements of a hydrogen gas system. The path dependency of changing the gas grids to systems that are compatible with hydrogen implies the need for the supply, storage, and demand of hydrogen to occur simultaneously. In the absence of a market and with the cost characteristics of hydrogen, supply and demand needs to emerge within modes of organization that ensure the security of supply and demand. The current connection obligation in combination with the existing investment incentives will not be adequate for supply and demand to emerge. Regulation in the emergence of supply and demand is unavoidable for the reliable functioning of the hydrogen provision. The role of the system operators is key in the coordination of the transformation of the grids and the emergence of the supply and demand. Currently, system operators cannot participate in any commercially related activities. It needs to be determined whether system operators can intervene in the emergence of supply and demand or possibly can participate in supply activities.

#### **5.5.5 Consumer sovereignty in the built environment**

End-users in the built environment have the right to be connected to both the electricity grid and the gas grid as a public service. With the replacement of natural gas as an energy carrier to provide heat, electricity remains the only directly available alternative<sup>10</sup>. Other alternatives to electricity require other parties to be involved. A district heating connection requires a district heating network to be constructed and exploited by several parties. Enough heat needs to be available at specific prices to make the network profitable and hence enough suppliers need to be connected. With a hydrogen gas grid connection, the gas grid needs to be adjusted to be compatible with hydrogen. In analogy with the district heating network, several parties need to be included and enough hydrogen and hydrogen suppliers should be available. The energy strategies that are part of the national policy, basically shift the choice in energy carrier from the individual consumer to the municipalities and hence to the concerned regions. The right to be connected to gas grids does not exist anymore and the individual choice to be connected to a

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<sup>10</sup> Excluding the buildings that are already connected to district heating, geothermal energy, or other heating alternatives to natural gas.

specific energy grid neither. Competition and therewith individual choice between grids are hard to establish. This effect is strengthened by the needed certainty for the emergence of the system (i.e. long-term contracts).

#### **5.5.6 Access regulations regarding the production and storages segment**

The natural gas production segment includes high entry barriers through public private partnerships and consist of a relatively small number of centralized producers. The production of hydrogen differs in nature from the natural gas production activities and can hence be organized differently. The challenge is to determine under what conditions access to the various hydrogen production technologies is allowed, on what scale. The latter will strongly determine how a hydrogen gas grid can develop in terms of the availability of supply at specific locations in the grid. The choice in specific entry conditions is essential for the development of specific hydrogen production technologies at specific locations. The latter is also applicable to the storage segment. The way in which the various production and storage facilities emerge and the way in which they are divided between the transmission and distribution grids determine the possibilities and constraints for the transaction of hydrogen.

#### **5.5.7 Transactions of local supply**

The local supply of biogas, injected as green gas, is currently connected to the distribution grids by means of a connection obligation and hence by bilateral supply and connection contracts with respectively the retail supplier and the DSO. The gas is transacted between the decentralized producer and the retail supplier and hence transacted between the retail supplier and the end-users. When the distribution grid becomes saturated because of a large share of local hydrogen supply, the gas needs to be transacted to other areas of demand. As described in section 5.4.8 technical adjustments to the grid will be necessary. The bilateral flow of gas needs to be accompanied with a way of transacting the bilateral capacity of the distribution grids. The retail model of gas transaction will hence not be adequate since it does only allow the transaction of bulk gas in the wholesale market. The local supply of gas needs to be transacted when the availability of large shares of supply shift to the level of the distribution grids.

#### **5.5.8 Connection and supply regime hydrogen system operators**

The connection and supply obligation of the distribution grid operators does not incentivize the emergence of local hydrogen suppliers (i.e. producers with an entry point in the distribution grids). The DSOs have an obligation to connect local gas suppliers but do not have the obligation to transport the local gas volumes. The connection and transport code hence state that a distribution grid operator only needs to transport the locally produced gas when it not exceeds the total momentary gas demand in a specific distribution grid. The latter implies the possibility of local suppliers to not being able to transport their gas. In analogy with the transmission grid, a mechanisms of transport capacity transactions should exist to ensure the local suppliers of transport capacity. Moreover, a transaction mechanism can incentivize the DSOs to invest in more (bidirectional) capacity.

### **5.6 Feasible Infrastructure design for the integration of hydrogen**

This section will first present a preferred hydrogen infrastructure design based on design choices in the design challenges that are identified. First, the preferred hydrogen infrastructure design will be presented along with the choices that are made. Second the rationale behind the choices will be discussed.

### **5.6.1 Choices in the main challenges of integrating hydrogen**

The gas infrastructure needs to integrate a new blue hydrogen gas production segment that is situated in between the natural gas fields and the gas transmission grid. The energy input of this segment will predominantly be based on natural gas that is coming from imports and extracted from the onshore natural gas fields. The transmission grid and distribution grids can be gradually transformed in phases regarding the availability of hydrogen supply. The remainder part of the transmission gas grid is hence still used for the provision of natural gas. The production segment, the gathering systems, and the storage system of natural gas stay intact. Both blue and green hydrogen are hence produced nearby the existing entry points. When hydrogen is produced offshore, the existing pipeline networks can be used to transport the hydrogen. The latter is dependent on availability of these networks and the possibilities of the discontinuation of the exploitation of the offshore natural gas fields. The trade-off that exist is to produce hydrogen offshore from renewable electricity surplus or onshore from natural gas. The former will most likely be more cost-efficient in terms of the marginal costs but will include lower yields than the latter. The advantage of a gradual approach is that the public grids can be transformed in an organized fashion. Since the dependence on natural gas allows to keep a large share of the gas buffer capacity of the system, hydrogen supply and demand can emerge gradually. The centralized system architecture allows for the integration of CCS infrastructure and the connections between the various supply chains needed to produce blue hydrogen. The downside of using natural gas to produce blue hydrogen is that the dependency on either the gas extraction or gas imports will not decline. Moreover, it will be difficult to transact natural gas alongside hydrogen gas without strict tariff regulations. Hydrogen will be unavoidably more expensive than natural gas without strict regulations. It will be hard to establish a regulatory framework where hydrogen replaces natural gas gradually in the gas grid and natural gas is only used for the purpose of facilitating the hydrogen provision. The latter will especially be hard considering the international nature of the natural gas market. Hydrogen will hence only become a viable replacement of natural gas when it can compete with the natural gas and electricity prices. A viable choice could be to adopt hydrogen only in the distribution grids as a mean to decarbonize the gas supply. The latter will imply that the provision of heat in the built environment becomes dominantly dependent on hydrogen gas instead of natural gas. Natural gas is still traded in the wholesale market and transported through the transmission grid. The transmission grid can hence gradually adopt hydrogen. Retail suppliers still buy natural gas but additionally contract enough hydrogen conversion capacity (i.e. steam methane reformation capacity). When hydrogen becomes competitive with natural gas it can be traded on the wholesale market alongside natural gas in kWh, irrespective of the gas quality. The obstacle of the latter is that the transport of hydrogen through the transmission grid will be dependent on transforming an entire part of the transmission pipeline network, including the connected entry and exit points. A high degree of regulation and coordination by the system operators and the government will hence be needed in the choices to convert the specific parts of the gas grid. The competitiveness of hydrogen and the transformation of the grids can be incentivized through the inclusion of CO<sub>2</sub> costs and the emergence of attractive hydrogen production prices.

The hydrogen gas infrastructure can be connected to the electricity grid infrastructure at locations where electricity surplus is available. The advantage of the coupling of these systems is that the gas system can function as the buffer of the electricity system. Hydrogen from electricity surplus will include relatively low marginal costs compared to the hydrogen from other production technologies due to the price of electricity surplus. A drawback is that enormous amounts of renewable electricity need to be available to ensure the energy input for electrolysis. Next to the availability of renewable electricity surplus, hydrogen can be produced from the surplus in the electricity grids due to saturation. The latter will enhance the buffer function of the electricity system but requires the electricity sector to adopt the same principles as the gas sector regarding the taxation of energy and emissions. Competition between the

electricity sector and the hydrogen gas sector would be unfair if grey electricity is still generated under lower CO<sub>2</sub> costs than hydrogen is produced. District heating networks can be included where they are an economic viable option. The coupling of the electricity, gas, and district heating systems would require the laws and regulations to change fundamentally, also on the European level. Investments in one sector need to be earned back in another and the externalities and investment costs should be able to be socialized over the various sectors. An integrated energy system hence is not viable to emerge on the short-term.

Since no market can emerge on the short-term, the wholesale market of gas should be based on the transactions of natural gas alongside with the transactions of hydrogen. Hydrogen can be traded alongside natural gas but only if the prices allow. The emergence of competitive hydrogen production technologies will hence determine how the transmission grid will be converted. Hydrogen can substitute natural gas in the transmission grids on the long-term when enough competitive supply and demand have emerged. The latter can be influenced by the European and national climate policies. The end-use segment in the distribution grid will only be allowed to combust hydrogen gas. Retail suppliers still buy gas on the wholesale market, but they are obliged to contract steam methane reformation capacity. The tariffs of the latter conversion capacities can potentially be included on top of the natural gas price in the market (i.e. an extra premium reflects the costs of the CO<sub>2</sub> emissions).

When the provision of heat to the built environment will become the energy service instead of the provision of gas or electricity due to the perspective of total efficiency gains and the need to socialize CO<sub>2</sub> and investment costs, the public service obligation shifts from a gas connection obligation to a heat connection obligation. The total system efficiencies, mainly in terms of costs, are hence the determinant for the alternative to natural gas. The heat provision to the consumers can either be dependent on a connection to the electricity grid, the gas grid, or a district heating network<sup>11</sup>. The choice in a specific connection is hence with the distribution system operators under supervision of the ACM. Consumers can choose their preferred alternative, provided that the distribution grids allow for the choice in terms of the total system efficiency. Distribution system operators can hence coordinate the development of the alternatives to natural gas in the distribution grids and the emergence of hydrogen supply and demand. The steam methane reformation conversion capacity on the distribution grid level is preferably publicly owned and operated or subject to highly regulated tariffs. When system operators would participate in the production of hydrogen gas, this would fundamentally change the role of the system operators. Consumers can still choose their alternative to natural gas, but within the boundaries of the distribution grids. The difference is that DSOs are not obliged anymore to expand a specific energy grid for the demand of a specific energy carrier, instead they can choose the most efficient path.

Access regarding the centralized hydrogen production activities is open under concessions. Access regarding the decentralized production of hydrogen is preferably publicly owned and operated. Privately owned and operated local supply can hence only emerge when the hydrogen is green, demand is available, and when the capacity of the gas grid allows (i.e. in analogy with the situation of green gas injection). The storage of gas on the short-term, will largely be based on the storage of natural gas. On the long-term, the underground storage of hydrogen can be organized centrally like it occurs with natural gas<sup>12</sup>. The transmission grid hence needs to be dominantly based on the transportation and storage of hydrogen. The local competitive production of hydrogen can emerge on the long-term when local

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<sup>11</sup> Excluding the individual heating systems that function without the interference of the grid.

<sup>12</sup> Only the Mining Act and SodM need to adopt the possibilities of the underground storage of hydrogen.

hydrogen production technologies become profitable and when the distribution grid topologies allow for it.

### **5.6.2 The rationale behind the choices in the provision of hydrogen**

The choice to produce blue hydrogen, predominantly from natural gas, in combination with CCS is made because no green hydrogen can be produced cost-effectively and on a large-scale in the short-term. A hydrogen provision that replaces the natural gas demand in the built environment will hence unavoidably be dependent on the steam methane reformation (SMR) of natural gas and the sequestration of CO<sub>2</sub>. SMR is a viable technology for the short-term, to produce hydrogen in large volumes, at relatively low cost. SMR can provide the hydrogen supply that is needed to develop a hydrogen infrastructure and therewith to address the enormous organizational challenge of transforming the Dutch gas infrastructure into a system compatible with hydrogen.

A hydrogen infrastructure will unavoidably be developed gradually, since it will be impossible within the current institutional system in the Netherlands to rigorously change the organization of the natural gas infrastructure. In our global oriented energy systems, hydrogen supply will only be developed when the energy prices allow for it and the demand for hydrogen is present. The development of a hydrogen infrastructure will hence be strongly dependent on where hydrogen can be produced cost-effectively, where the demand for hydrogen will emerge, and how the supply can be buffered and transported.

The natural gas infrastructure cannot be fully transformed on the short-term, because the natural gas infrastructure will partly be needed to provide natural gas to produce hydrogen. The Dutch gas transmission system can hence not be fully used to transport hydrogen. Moreover, the natural gas buffer capacity and hence the natural gas infrastructure is needed for the security of supply in the absence of adequate volumes of hydrogen production and buffer capacities. Natural gas will not only function as the energy input to produce hydrogen, but it will also help in realizing a hydrogen infrastructure that still address the important performance criteria of the gas infrastructure.

The transformation of the public distribution grids needs direction because of the nature of the individual end-users. The installation of end-use equipment in the service sector and residential sector buildings is an enormous organizational challenge. The public grids and the hydrogen supply need to be developed accordingly. The transformation of the public grids, the development of hydrogen supply capacity, and the installation and realization of hydrogen demand will unavoidably need a high degree of coordination and direction. Public interference is hence inevitable, and the individual choice of the consumer regarding a grid connection cannot be safeguarded, since it will be troublesome to establish individual contracts per end-user.

Without clear governmental policies regarding the use of hydrogen in the public gas grids, a hydrogen system will not emerge on the short-term. The choice to provide hydrogen gas through the entire gas distribution grid is based on the notion that the combustion of natural gas in the built environment cannot be decarbonized. The direction of the government can cause hydrogen to become an equivalent option to all-electric solutions. The new gas standards and laws and regulations will therewith need to be based on hydrogen gas for the use in the end-use equipment of the end-users.

The functioning of a hydrogen gas infrastructure and the functioning of the electricity infrastructure cannot be considered separately. The production of green hydrogen will be based on the available renewable electricity surplus and will hence provide a means to buffer electricity. The dependency of the green hydrogen production on the renewable electricity surplus is based on the notion that the direct



utilization of electricity is more efficient in terms of its energetic performances. To produce the adequate volumes of green hydrogen to replace the blue hydrogen supply, enormous capacities of renewable electricity generation must be available. These capacities will not be available within the short-term in the Netherlands.

The interwovenness of the electricity and gas markets becomes more intensive due to the possibility to produce hydrogen from both natural gas and electricity. On the short-term, in the current market design, it will be impossible for green hydrogen to compete with electricity. The same applies to the competition between blue hydrogen and natural gas. The possibility to produce hydrogen from natural gas and electricity causes the external effects of the electricity sector to influence the gas sector more intensive (and vice versa). Investments in renewable electricity capacity can for example be earned back in the provision of hydrogen. The borders of the individual energy systems partly fade away and the need for the public DSOs to consider an integrated energy system without the competition in between the distribution systems arises. Laws and regulations should address the perspective of integrated energy systems.

A gas wholesale market that is fully dependent of the transactions in hydrogen cannot emerge on the short-term. When hydrogen gas is traded alongside natural gas, hydrogen supply can emerge where the price allows. The competitiveness between hydrogen gas and natural gas will mainly be dependent on the CO<sub>2</sub> prices, the natural gas prices, and the developments in the hydrogen production technologies. The latter tariffs can be influenced by governmental and European policies. Energy will be traded irrespective of the specific energy carrier. The traded energy needs to be converted to the energy carrier where the transport and end-use is compatible with. Such a market model is strongly dependent on the regulation of the energy tariffs and the gas qualities in the public grids. Blue hydrogen from SMR can only compete with natural gas when the CO<sub>2</sub> price is higher than the costs of integrating CCS. Green hydrogen is unable to compete with blue and grey hydrogen on the short-term due to its capital costs.

The regional energy strategies are shifting the individual choice of the consumer to a collective choice at the municipal level in the defined energy regions. The latter unavoidably shifts the perspective from individual choice to the most efficient option to replace natural gas in an area. Competition in between the distribution systems will hence become irrelevant. The total energy distribution system might benefit from the integration of these systems and the possibilities to socialize the costs over the entire systems.

### 5.7 Alignment in current infrastructure design because of the integration of hydrogen

This section aims to discover the role of alignment in the identification of the design challenges regarding the integration of hydrogen. The operationalization of the design issue, as delineated in chapter 2, is applied to both hydrogen infrastructure options to discuss the possible role of alignment in the existence of the design challenges. The categorization of the current natural gas infrastructure design is presented in Table 18, adopted from chapter 3.

	Technical operational activities		
<b>Layer of abstraction</b>	<b>Access</b> (allowed to participate)	<b>Responsibilities</b> (control and intervention tasks)	<b>Coordination</b> (centralized vs decentralized)
<b>Perspective</b>			

Production	Access through Property rights infringement	Delegated responsibility	Decision rights infringement
Transmission	Closed access	Public responsibility	Public entity coordination
Distribution	Closed access	Public responsibility	Public entity coordination
Storage	Conditional access	Delegated responsibility	Decision rights infringement
<b>Market activities</b>			
<b>Layer of abstraction</b>	<b>Access</b> (state vs market)	<b>Responsibilities</b> (Ownership & decision rights)	<b>Coordination</b> (Vertically integrated vs market)
<b>Perspective</b>			
Production	Delegated access	Public-private responsibility	Public-private coordination
Transmission	Closed access	Public responsibility	Public coordination
Distribution	Closed access	Public responsibility	Public coordination
Storage	Conditional access	Public-private responsibility	Public-private coordination

Table 18: Categorization of natural gas infrastructure design for the purpose of assessing alignment, adopted from chapter 3

When hydrogen option 1 and option 2 are integrated, the above categorization changes in terms of the organization of the technical-operational activities regarding the production segment. The new gas production segment can include a variety of conversion processes from various energy sources. The new segment is not as uniform as the extraction of natural gas and can allow more entities to participate in. There is no need for the strict regulatory entry barriers as with the mining activities. From this changing production segment, it can be argued that the access layer is disaligned because of the integration of hydrogen. New hydrogen institutions must be adopted to align the new hydrogen production segment with the institutional environment. The categorization does not indicate other forms of disalignment.

## **6. Discussion**

This chapter elaborates on the discussion of the research results in section 6.1, the theoretical discussion in section 6.2, and the reflection on the research method in section 6.3.

### **6.1 Discussion on the research results**

The results of the research can be separated into four distinctive categories. First, the chosen hydrogen infrastructure configurations. Second, the identified change and the design challenges because of the integration of hydrogen. Third, the potential design choices in a future hydrogen infrastructure design. And Fourth, the role of alignment in determining the design challenges. To conclude, the uncertainties of the research results and the possibilities for future research will be discussed.

#### **6.1.1 Discussion on the chosen hydrogen infrastructure configurations**

The two chosen hydrogen infrastructure configurations assume that hydrogen will be transported through the existing pipeline networks of the natural gas grid to the Dutch residential and service sector. The analysis therewith focusses on the provision of hydrogen through the existing pipeline networks without including other end-use sectors than the residential and service sector. The two alternatives give useful insights on the applicability of the natural gas infrastructure to function with a highly centralized supply of gas and a highly decentralized supply of gas. The two chosen hydrogen infrastructure configurations therewith adequately capture the possibilities for the provision of hydrogen through the existing infrastructure but oversimplify the possibilities for energy demand reductions and the possibilities of replacing natural gas by other alternatives. The latter oversimplification can bias the results in terms of the exaggeration of the natural gas demand that will be replaced by hydrogen.

#### **6.1.2 Discussion on the identified change and design challenges posed by the integration of hydrogen**

The needed changes in the gas infrastructure design because of the integration of hydrogen identify how the design of the natural gas infrastructure is not adequate anymore regarding the variables of the comprehensive design framework. Moreover, they help with the identification of the design challenges. Adequate refers to the way in which elements need to be replaced or added to the infrastructure design to allow for an integration of hydrogen. The comprehensive design framework is used to assess the design challenges that appear in between the technological and institutional design of the natural gas infrastructure because of an integration of hydrogen. The latter allows for the identification of the design challenges regarding the internal consistency of both dimension of the comprehensive design of the gas infrastructure. With the identification of these consistency challenges, insights are gained in how the design of one variable should relate to another and vice versa. These results are qualitative results that does not include possible feedback effects over time. Instead, they illustrate an assessment on the applicability of the existing system design and economic institutions for the provision of hydrogen following the formulated hydrogen infrastructure configurations.

The results can be biased in terms of the interpretation of the semi-structured interviews and the expertise and opinions of the interviewees. Moreover, the future energy systems include a high degree of uncertainty in their development. The role of hydrogen in the future energy systems is hence unsure. In the thesis project, hydrogen is assumed to be a viable option to replace natural gas in the current gas infrastructure. The latter implies that hydrogen will be utilized to replace a large share of the natural gas demand. This assumption can bias the results since the identified changes are focused on a near total replacement of natural gas by hydrogen in the existing infrastructure. Developments in the design of future energy systems and their influence on the design challenges that are identified are hence mainly

neglected. Possible interaction effects, future developments, and the possible feedback effects over time are also neglected.

The changes because of an integration of hydrogen are mainly caused by the characteristics of a starting gas infrastructure system with a new gas production segment that needs to transport, store, and use another quality of gas. The changes in the design variables are hence mainly caused by the new production segment and the new characteristics of the produced gas that introduce new requirements to the technical operation of the system. The changes in economic institutions are largely triggered by the characteristics of a starting infrastructure system with an immature market and high up-from investment costs.

The most intensive changes in the system design are needed regarding the instalment of hydrogen production capacity, storage capacity, and end-use equipment. The transportation infrastructure can be changed relatively easy in terms of costs. The interaction between the evolvement of an adequate supply (i.e. production, storage, and transport capacity) and demand will be most challenging. The changes in the economic institutions require laws and regulations to change regarding various energy systems. The latter will be a complex and time-consuming activity including a variety of public and private actors. Since the utilization of hydrogen in the public gas grids is prohibited, changes in laws and regulations need to precede the changes in the technical system. The system design challenges and the challenges in economic institutions can hence mainly be explained by the following issues:

- the integration of a new gas production segment,
- the dependency on the design of the current gas infrastructure for the future provision of hydrogen,
- the requirement to decarbonize the gas production and end-use,
- the inexistence of a hydrogen economy,
- the large buffer capacity of the current system that is largely based on the extraction of natural gas,
- the potential shift of the gas supply from the transmission grids to the distribution grids,
- and the potential gains of integrating hydrogen from a total energy system perspective.

The future role of hydrogen in the heat provision of the built environment is dependent on the emergence of hydrogen supply and demand, and hence the transformation of the public gas grids. Uncertainty in the laws and regulations regarding the provision of hydrogen and the development of the production technologies make the role of hydrogen in the provision of heat to the built environment unsure. The possibilities of demand reduction measures and other alternatives to gas in the provision of heat contribute to this uncertainty. Alternatives such as all-electric and geothermal heat are already applied in buildings that are built and renovated and building envelopes can still be improved.

### **6.1.3 Discussion on the presented hydrogen infrastructure configuration**

The hydrogen infrastructure configuration that is presented as a potential solution to successfully integrate hydrogen on the short-term represents a potential design of the gas infrastructure that does not include severe internal consistency problems and negative path-dependencies. The design challenges regarding both hydrogen infrastructure options are included in the potential design. The presented design hence illustrates a potential configuration for the provision of hydrogen when it fully replaces natural gas in the distribution grids.

The presented hydrogen infrastructure configuration is next to the possible incompleteness of the included design variables and the static approach, also subject to the bias of the researcher and the interviewees. Bias could exist in the delineation of the research due to the assumption about the future role of hydrogen in the energy provision to the built environment. Another assumption that could bias the results is that natural gas will be replaced by hydrogen in such a way that no direct CO<sub>2</sub> emissions are allowed in the end-use of gas and in the production of hydrogen. Moreover, it is assumed that natural gas will still play a key role in the production of hydrogen on the short-term.

The presented infrastructure configuration is largely based on the notion that vertically and horizontally integrated distribution grids, in which DSOs get more intensive roles, are necessary on the short-term. The choice is based on the idea that this model is needed to successfully replace the natural gas connections for efficient alternatives, while addressing the total energy system efficiency. Moreover, such an approach would allow for the socialization of the large up-front investment costs of the infrastructure and the costs of the decarbonization of the gas provision. The decarbonization of the gas provision becomes a more important goal than the total system costs, the persistence of the independency on natural gas, the possibility for competition between the electricity, heat, and gas grids, and the consumer sovereignty regarding specific energy carriers in the built environment. It is hence assumed that these latter goals can exist on the long-term in a more developed system and market.

The specific political choices and the development of the hydrogen technologies determine to a large extent if hydrogen will become an alternative to natural gas in the heat provision to the built environment and especially on what time frame this will happen. The presented design choices do not say something about how hydrogen will be integrated in the gas infrastructure. Instead they present a set of choices that can be made to successfully integrate hydrogen in the existing gas infrastructure on the short-term to start addressing the policy targets in 2030 and 2050.

#### **6.1.4 Discussion on the assessment of alignment**

The results on the categorization (i.e. application of the operationalized design issues) of the organization of the production, transmission, distribution, and storage activities do not adequately explain the degree of alignment in the current natural gas system or the degree of alignment because of the integration of hydrogen. The results do not explain the role of alignment within the functioning of the current gas infrastructure. The disalignment that results from the integration of a new hydrogen gas production segment seems rather obvious. The assessment of alignment through the further categorization does hence not give useful insights on how the system is aligned or how the system should be changed to achieve alignment.

#### **6.1.5 Uncertainties in the research results and the possibilities for future research**

The thesis project focusses on the techno-operational and economic-institutional implications that an integration of hydrogen can cause for the functioning of the Dutch gas infrastructure. The focus of the research is therewith mainly on the organizational challenges of an integration of hydrogen for the functioning of the gas provision. An assessment on the costs and environmental performance of the hydrogen infrastructure is excluded from the scope. Acceptability issues regarding the transformation of hydrogen are also excluded and the detailed hydrogen infrastructure design and performance are not addressed. The focus of the research does not include the interaction of a hydrogen system with possible acceptance issues regarding the hydrogen end-use technologies, the CCS infrastructure, the natural gas dependency, and the infringement of consumer sovereignty. Moreover, it is unsure under what specific market design hydrogen supply and demand will occur. Next to the market design it is unsure how the

detailed systems of the hydrogen gas production segment and the hydrogen buffer capacity should be designed and what the effect is of a replacement of gas by hydrogen on the total system costs and the security of supply. The possibilities of merging the district heating, hydrogen gas, and electricity distribution systems are unsure regarding the effect on the total system efficiency in terms costs and energy availability. It is unsure how such a merged system fits within the current European and national laws and regulations for the upcoming years. The uncertainty regarding the development of the hydrogen production prices in the future introduces uncertainty regarding the specific possibilities of the adoption of the technologies. The following suggestions for future research can potentially address the uncertainties around the results of the thesis project:

- Under what conditions will hydrogen condensing boilers and hydrogen fuel cell technologies be adopted in the built environment?
- Under what conditions and on what scale will the integration of CCS infrastructure be acceptable?
- How are end-users in the built environment valuing consumer sovereignty?
- Under what conditions and on what scale will the natural gas dependency be acceptable?
- What will be the diffusion rate of sustainable gasses in the replacement of natural gas in the built environment?
- What market designs enhance the emergence of hydrogen supply and demand on the short-term?
- What is the effect of replacing natural gas by hydrogen on the affordability and availability of the gas provision?
- What does a detailed design of a hydrogen production segment look like that addresses the environmental policy targets and the security of supply?
- What does a detailed design of a gas storage segment look like when the public gas grids are strictly compatible with (near) 100% hydrogen gas?
- What is the effect of the integration of the district heating, hydrogen gas, and electricity distribution grids on the total system costs and the total buffer capacity?
- What are the needed regulatory alterations to allow for integrated energy systems in the Netherlands?

## 6.2 Theoretical discussion

The thesis project aimed to contribute to the knowledge about alignment (i.e. coherence) between institutions and technology in energy infrastructures. Crettenand & Finger (2013) refer to the notion that the institutions in a network industry (i.e. infrastructure) need to be aligned to reach the defined system performance. The defined system performance is therewith mainly dependent on the specific political choices and therewith the political trade-offs that are made between technical, social, operational, environmental, and economic performance categories (Crettenand & Finger, 2013). The research conducted in the thesis provided the insight that change in an energy infrastructure is constrained by the degree to which the institutions of the system can be aligned over time and political preference. The emergence of public hydrogen gas grids is for example constrained by the possibilities of the development of the technical system, the economic institutions, and their interaction over time.

Crettenand & Finger (2013) argue that alignment between institutions and technology can be evaluated along the technical, social, operational, environmental, and economic performance criteria as defined by Crettenand, Laperrouza, Finger, & Duthaler (2010). Moreover, Crettenand & Finger (2013) hence recognize that alignment can partly explain the performance in a network industry and that the other part is explained by the individual technological and institutional systems. The research in the thesis

supports the notion that alignment is important for the total system performance by recognizing the importance of the internal consistency of the economic institutional and technological variables (i.e. striving for alignment between institutions and technology). The research conducted in the thesis however also recognizes that alignment can be defined as one of the goals of a socio-technical system approach and therewith cannot be evaluated properly along the five performance indicators. In line with a socio-technical system approach<sup>13</sup> as defined by Bauer & Herder (2009), the evaluation of alignment would require to identify the effects of the interaction between the institutional and technical variables on the performance of the total system. The concept of alignment as an indicator of the outcome of the total system hence remains fuzzy. Alignment as the explanation of the malfunctioning of an energy infrastructure is therewith troublesome.

The research conducted in the thesis project aimed to contribute to the insights on how to better attune the technical and institutional design of energy infrastructures. By the further operationalization of the alignment issue, the research aimed to contribute to the insights in how a certain degree of alignment could help the total system to be better attuned. The application of the new categories of alignment did not give useful insights in how to better attune the system and economic institutional designs based on a certain degree of alignment. The concept of alignment is currently based on the alignment between institutions and technology in the total system. When alignment is investigated on a more detailed level, the concept seems to get fuzzier and therewith less useful. The concept alignment as a determinant on how to better attune the technical and institutional systems is hence troublesome without the further operationalization of how the variables in an energy infrastructure should be aligned.

Next to the role of alignment in better attuning the system and economic institutional design of energy infrastructures, the further operationalization of the alignment issue also aimed to contribute to the knowledge about the conceptualization of the interaction between both design dimensions. The further operationalization seems promising in terms of the possible conceptualization of the relationship between institutions and technology. The application of the categories did provide useful insights in how the relationship can be further operationalized. However, the application of the new categories did not provide insights in how alignment or disalignment between institutions and technology cause potential malfunctions in the gas system.

### **6.2.1 Discussion on the application of the comprehensive design framework and the function of alignment in the analysis**

In the thesis the comprehensive design framework (CDF) of Scholten & Künneke (2016) is applied as a tool for the conceptualization of the natural gas infrastructure within the concept of socio-technical systems. Moreover, the CDF is applied as a tool to analyze the potential technical and institutional design challenges because of the provision of hydrogen through the existing natural gas infrastructure.

The conceptualization of the natural gas infrastructure through the application of the CDF was challenging in terms of the composition of the defined variables. The formulation of the content of the variables, as defined by Scholten & Künneke (2016) in the CDF, is not comprehensive. The demarcation of the variables is hence open to a lot of interpretation space and therewith difficult to conduct. The internal consistency of the demarcations of the various variables hence becomes challenging and open to the possibility of interpretive bias of the researcher. The CDF functions therewith mainly as a tool to structurally map an energy system as a socio-technical system in a way that safeguards the possibility

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<sup>13</sup> The need for jointly optimizing the technical and social arrangements of a socio-technical system. (Bauer & Herder, 2009).

of excluding important system elements and their interrelations. The CDF, however, does not provide adequate means on how to describe the variables and their interrelations. Alignment is therewith also difficult to assess, since the framework does not provide the concepts of how variables should be related. In the formulation of the potential hydrogen infrastructure configurations that were used for the assessment on the applicability of the natural gas infrastructure to provide hydrogen, the CDF did not provide useful concepts to determine how the hydrogen infrastructure configurations should be designed. The CDF is hence less applicable for the mapping of new system elements. Instead, it provides a useful tool to map the change that is the result of the integration of new system elements in an existing system. The CDF provides the means for the identification of the new and changing system elements when the existing system is conceptualized properly. The difficulty of the application of the CDF is therewith mainly on the conceptualization and demarcation of the energy infrastructure under study. Once the conceptualization is conducted and the new system elements are defined, the CDF is a useful tool to determine where system elements need to be added or replaced. The description of the energy infrastructure within the variables of the CDF can hence be assessed structurally per variable. The design challenges can be deviated from the interpretation of the consequences of the identified system elements that need to be added and replaced. The CDF does not provide any direction in how to assess the consequences of the interrelations between variables.

Alignment between the design dimensions and the layers of abstractions is a useful concept to contemplate about possible obstructions for the integration of new system elements and the change of existing system elements for the overall functioning of the system. In combination with the strength of the CDF to structurally map the variables and hence the changing system elements, the concept of alignment provides the means to identify possible design challenges and design options. The application of the concept of alignment is however particularly challenging due to the lack of clarity on its definition. Alignment is a useful concept to analyze an energy infrastructure design under change and helps to think about possible obstructions in the changing design. On the other hand, alignment is not operationalized and does not provide any grip on how variables should be related or designed. The CDF in combination with the concept of alignment therewith provides a tool to check, in a structured manner, how an existing energy infrastructure is designed. From this perspective it aids in overseeing the broader perspective of energy infrastructures as socio-technical systems and hence helps to capture energy systems in the concepts of socio-technical systems. The CDF has not proven to be an adequate tool to identify how an energy system changes because of the integration of new system elements, what the consequences are, and how they can be solved. It rather functions as a tool to keep track of the system changes because of the integration of new system elements. Moreover, the CDF helps to think about the consequences of these changes for the overall system performance.

### **6.2.2 The layers of the comprehensive design framework**

Layer 2a of the economic institutional dimension in the comprehensive design framework refers to “how the political-bureaucratic system works, how state–society relations are framed, and how the rule of law is exercised.” (Scholten & Künneke, 2016, p. 11) The latter cannot be adequately linked to what is defined by Scholten & Künneke (2016, p. 9) as “the perspective on system architecture and asset characteristics, such as whether the system is or should be open or closed and centralized or decentralized in nature and what generation, transport and storage, application technologies (should) make up the assets of the infrastructure.” The linkage of these layers is problematic since the scope of the polity, judiciary, and bureaucracy variables does not match the scope of the system architecture and asset characteristics variables. The system architecture and asset characteristics in the gas infrastructure differ from those in the electricity infrastructure while the political-bureaucratic system remains the same. Competition law however can be related to the design perspectives. Moreover, it can be argued



that the formal institutions of a system are the sector laws and decrees. The Gas Act and the Mining Act can therewith be placed in layer 2a instead of layer 2b. The latter formal institutions are linkable to the design perspectives of the technological design.

### **6.2.3 Environmental value of energy infrastructure design**

One could argue that the CDF not properly addresses the environmental degradation that energy infrastructures cause. The technological dimension in the CDF includes the technical design of energy infrastructures from an engineering perspective and is framed as a dimension that is mainly focused on the technical and operational functioning of the system. The economic-institutional dimension in the CDF includes all the laws and regulations that needs to address the social, economic, and environmental functioning of the system. Technology and institutions can hence be designed. Based on the ideas of infrastructure ecology of Pandit et al. (2017) it can be argued that technology and institutions should not only be designed to address the above mentioned values, but also to integrate, complement, and where possible, regenerate the natural ecological systems. From this perspective, it could be argued that the conceptualization of energy infrastructures in the CDF misses the inclusion of natural ecological systems and hence the ability to design and achieve an energy system that includes the relationships between the technical design and the natural ecosystems, and between the economic-institutional design and the natural ecosystems. In line with the rationale behind the CDF it can hence be argued that the neglect of the natural ecosystems in the conceptualization of energy infrastructure design practices, can lead to unforeseen implications of technical and institutional design choices on our natural ecosystems (and vice versa). Alignment will therewith also need to exist in between the technological system and the natural ecosystem, and in between the economic-institutional system and the natural ecosystem. The latter seems problematic since it is hard to design natural ecosystems. Defining natural ecosystems within the three layers of abstraction of the CDF is hence troublesome but challenging.

### **6.3 Reflection on the research method**

The main objective of the research is defined as, *to identify and address the challenges that the integration of hydrogen in the Dutch natural gas infrastructure can cause for the provision of heat to the Dutch residential and service sector.* The research in the thesis did identify an extensive list of possible challenges that the integration of hydrogen causes for the functioning of the current gas infrastructure design. By the identification of the consistency between the design challenges and by the formulation of a potential hydrogen gas infrastructure design, the thesis aimed to address the identified design challenges. The research method hence contributed to the identification of the design challenges and the identification of the consistency needed between the technological and institutional variables to overcome the specific design challenges.

The application of the comprehensive design framework aided in the structured mapping of the system and economic institutional design of the natural gas infrastructure. The framework hence allowed for the identification the design challenges, and the identification of the consistency between the identified challenges in a structured manner. It however did not provide the means to determine how the identified challenges should specifically be addressed. Only the consistency between the design challenges and therewith the dependency between specific variables in solving a challenge could be identified. The framework is less applicable regarding the actual design of a new energy infrastructure and does not provide the means to consider which of the various design solutions is the most adequate in addressing a design challenge. The framework can mainly be used to assess if a design introduces potential challenges to the functioning of an existing system and therewith identify the important dependent

variables for a specific design challenge. The framework it is not an adequate tool in discovering how the system should be designed.

The semi-structured interviews did fairly contribute to both the identification of the changes and the identification of the design challenges because of the integration of hydrogen. With more interviews that include a larger variety of actors from diverse backgrounds, the insights might have been more valuable. The time constraints of the thesis project did not allow for more interviews and a choice needed to be made in the interviewees. Potential hydrogen producers, storage operators, GTS, Gas Terra, and other DSOs would have been interesting to interview.

The research method did not give extensive insights in how to specifically design the system to solve the identified challenges. The method used is hence not adequate for design due to its qualitative and static nature and lack of detail. For the design of a new gas infrastructure, deeper understanding is needed about the identified challenges and their impact on the performance of the system. A system dynamics approach might be useful to investigate the magnitude of the identified design challenges and hence the way in which they influence each other and finally the total system performance.

## 7. Conclusions

The Dutch climate policy to replace natural gas in the residential and service sector implies that the existing natural gas infrastructure either needs to be decommissioned or a sustainable alternative to natural gas needs to be integrated. The Dutch natural gas infrastructure is the most comprehensive energy infrastructure in the Netherlands regarding the energy transportation and buffer capacity. The decommissioning of such a system would hence have severe consequences for the reliability, affordability, and acceptability of the energy provision in the Netherlands. This study aimed to get insights on the applicability of the Dutch natural gas infrastructure to replace natural gas with hydrogen gas in the provision of heat to the Dutch residential and service sector. This research therewith provides an analysis on the changes that are needed in the current natural gas infrastructure design because of the use of hydrogen. Moreover, the research investigates the potential technical-operational and economic-institutional challenges for the design of a gas infrastructure that provides hydrogen gas to the residential and service sector to satisfy their heat demand. The main research question is therefore defined as follows:

*How to successfully integrate hydrogen into the current natural gas infrastructure and guarantee the adequate provision of energy to the Dutch residential and service sector?*

The research questions that are formulated to provide an adequate answer to the main research question are defined as follows:

1. How can the Dutch natural gas infrastructure be conceptualized in terms of the concepts of socio-technical systems?
2. How are the technical system and the market of the Dutch natural gas infrastructure designed and what does this mean for the complementarity within the socio-technical system?
3. What hydrogen infrastructure configurations are feasible to replace natural gas in the Dutch natural gas infrastructure for the heat provision of the residential and service sector?
4. What implications do the integration of the hydrogen configurations have on the functioning of the natural gas infrastructure?
5. What are convenient alterations in the design of the natural gas infrastructure to deal with the implications of the integration of the hydrogen infrastructure configurations?

### 7.1 The comprehensive design framework and alignment in the conceptualization of the natural gas infrastructure and the design challenges

The thesis applied the comprehensive design framework (CDF) of Scholten & Künneke (2016) as a tool for the conceptualization of the natural gas infrastructure within the concept of socio-technical systems. Moreover, the CDF is applied as a tool to analyze the potential technical and institutional design challenges because of the provision of hydrogen through the existing natural gas infrastructure. The CDF has proven to be a useful tool for the completeness of the description of the natural gas infrastructure within the concepts of socio-technical systems. The CDF is less helpful in the actual description of the variables in the natural gas infrastructure and functions mainly as a checklist for the conceptualization of an energy infrastructure and not as a tool to describe the actual system. The CDF is therewith useful to assess the changing system elements in an existing energy system but less to analyze the consequences of the change. The concept of alignment in combination with the CDF has proven to be useful for the identification of potential design challenges in between the technical system design and the design of the economic institutions. The CDF is less useful for the identification of

potential design challenges within the technical system design dimension and the economic institutional design dimension themselves. The CDF can use improvements in the operationalization of how the various variables in both design dimensions should be related to each other. The further operationalization of alignment did provide useful insights in how to conceptualize the relationship between institutions and technology. It did not explain the role of alignment as a determinant in the functioning of the gas infrastructure. The concept of alignment as a design goal remains rather fuzzy. The alignment between institutions and technology is hence relevant to strive for but still hard to assess or use in relation with the total system performance.

## **7.2 The Dutch natural gas infrastructure design**

The technical system of the gas infrastructure is mainly designed based on the liberalization of a vertically integrated monopoly that was built upon on the specific characteristics of the available volumes of natural gas, the present gas qualities, the public service characteristics of natural gas, and the possibility of natural gas buffer capacities in the Netherlands. The latter determinants have resulted in a centralized natural gas infrastructure based on the top-down provision of gas in which the assets comply with specific gas quality standards. The network topology and buffer capacity are based on the centralized production and storage of large volumes of natural gas. The management of the gas transportation infrastructure is strictly regulated and conducted by the public system operators. The decisions regarding the natural gas mining activities are regulated by the government. The demand for natural gas and hence the network topology is basically stemming from the legal obligation to connect all the Dutch buildings to the public natural gas grids.

The market design of the gas infrastructure is based on the functioning of the publicly owned and operated transmission and distribution grids. The wholesale market is basically facilitated by the transmission grid and the retail market by the distribution grids. The wholesale market is designed to allow every competent actor that is willing to trade gas to participate under the rules of the TSO and the regulator. The wholesale market is hence designed to allow for the competition in bulk gas, to enhance the security of supply, and to address the public service obligation connected to the natural gas provision. The retail market is designed to supply the smaller consumers that are not interested to be active in the trade in natural gas. Basically, the retail market allows the consumers to buy gas competitively. The competitiveness in the retail market is based on the ability of the retail suppliers to strategically buy gas in the wholesale market and resell it to the small-scale end-users. The retail market therewith enhances the market functioning of the wholesale market but only allows for the unilateral transactions of gas. The supply that is injected in the distribution grids is hence also unilaterally traded for regulated prices.

## **7.3 Conceptualization of hydrogen infrastructure configurations**

The design and operations of the current natural gas infrastructure are comparable to the hydrogen infrastructure configuration that follows from the large-scale centralized production of hydrogen. The decentralized production of hydrogen is more comparable to the development of the local production and injection of biogas. The Dutch natural gas infrastructure is designed to function with large-volumes of centrally produced gas that are distributed through the transmission grid to the distribution grids. The locally injected volumes of natural gas in the distribution grids are hence marginal. The hydrogen infrastructure configuration based on a large share of decentralized produced hydrogen gas hence includes significantly different operational requirements regarding the flow of natural gas through the transmission and distribution grids. The decentralized option deviates therewith more from the current provision of gas than the centralized option.

#### **7.4 Change posed by the integration of hydrogen**

The provision of hydrogen through the natural gas grid implies that certain elements of the existing system need to be replaced or that elements need to be added. Technically, it is important that a new hydrogen gas production segment will be added, and that the energy buffer capacity needs to be organized differently. The provision of hydrogen through the public grids hence includes the need to replace the current compression and metering stations. The need to produce blue hydrogen from natural gas introduces the need to install new CCS infrastructure. The current natural gas end-use equipment is not compatible with the handling and combustion of hydrogen and need to be replaced by alternative end-use equipment. A new odorant needs to be added and the safety instructions and detection apparatus needs to be changed. A large share of decentralized produced hydrogen gas in the absence of enough local demand will require the current network topology to be changed. New hydrogen pipeline networks can be constructed, or boosters can be installed that allow for the bilateral flow of gas. The latter adjustments are causing a more cost-intensive and complex grid operation.

Institutionally, it is essential that the existing laws and regulations need to be reformulated to allow for the provision of hydrogen through the public gas grids, and that hydrogen needs to be transacted under established gas quality standards. The Dutch Gas Act and the energy codes need to be reformulated, and new industry standards need to be established based on the new hydrogen gas quality standards. The Mining act needs to be reformulated to realize the underground storage of hydrogen. New market arrangements need to be established to transact hydrogen alongside natural gas and the current market model needs to be assessed on its ability to ensure hydrogen investments. The availability of large volumes of local gas in the absence of local demand imply the need to transport the gas to other areas of demand. The current market model and grid topology are not adequate to facilitate the transport and transactions of large volumes of gas injected in the distribution grids.

#### **7.5 Design challenges of integrating hydrogen in the natural gas infrastructure**

The technology to produce, store, transport, and consume hydrogen is already available but not yet installed for the purpose of a public hydrogen provision. The market design and the laws and regulations need to fit the upcoming design of the hydrogen gas provision. When hydrogen gas will be produced centrally, in large volumes, and be transported through the existing infrastructure, design challenges will predominantly occur in the establishment of enough hydrogen supply and demand, the reformulation of the Gas Act and the energy codes, and the design of the phase out of the natural gas provision in combination with the development of the hydrogen provision. When the production segment of hydrogen gas adopts a more decentralized character, these design challenges will be complemented with the challenge to adjust the grid design and operations to a shift in gas entries in the transmission and the distribution grids. The market model and the laws and regulations will hence need to change more rigorously.

The establishment of enough supply and demand is hard within the current market design due to the inability of blue and green hydrogen to compete with the existing natural gas and electricity prices. The market is not able to provide proper investment signals yet. The reformulation of the laws and regulations regarding the provision of gas to the residential and service sector will be challenging. The decision-making process will include a variety of public and private actors both on the national and international level. The transformation of the natural gas grid to a hydrogen grid will need to occur strictly organized. With a market design that allows hydrogen supply and demand to emerge where it is a cost-efficient option, the system transformation still needs to be organized to secure the total system

functioning. The design challenge is to determine how the system will be transformed over time, under what conditions, and under whose authority.

## **7.6 Convenient alterations in the design of the natural gas infrastructure**

It will be difficult to transform the total natural gas infrastructure to be compatible with hydrogen due to the remaining dependency on natural gas, the CO<sub>2</sub> costs that are not integrated in the energy prices, the inexistence of hydrogen supply and demand, the higher energy prices in other end-use sectors, the replacement of natural gas by other alternatives, and the inexistence of laws and regulations addressing the provision of hydrogen through the public gas grids. The emergence of a hydrogen system on the short-term will hence be unavoidably dependent on the regulatory intervention in certain design choices. These choices need to be made for the total gas infrastructure system. The gas quality standards of the public gas grids and the flexibility in gas standards will need to be formulated. The use of natural gas can only be allowed when the CO<sub>2</sub> that is emitted is sequestered and stored or re-used. Consumers in the residential and service sector will have the right on the provision of heat, irrespective of the energy carrier. Steam methane reformation will function as a natural gas conversion process to obtain the right gas quality for the distribution of hydrogen gas and to facilitate the sequestration of CO<sub>2</sub>. The market for natural gas will stay intact and hydrogen gas will only be transacted in the wholesale market if the price allows.

## **7.7 Successfully integrating hydrogen in the natural gas infrastructure**

A successful integration of hydrogen in the natural gas infrastructure will require quick adjustments in the laws and regulations around the provision of gas through the public grids. Hydrogen cannot be considered a proper substitute to natural gas if it is legally not possible to provide hydrogen through the public gas grids. The government should be clear towards 2030 about the future of the hydrogen provision. Without a clear direction, hydrogen cannot substitute natural gas within the residential and service sector. Hydrogen will eventually need to be established as a new gas standard within the Dutch distribution grids. The path towards hydrogen as a new gas standard needs to be determined. Besides the enabling of the hydrogen provision in the laws and regulations, hydrogen requires enormous investments to establish enough hydrogen supply and demand. These investments cannot emerge within the current market model and therewith imply that the government will need to make strict and costly measures to realize a hydrogen system on the short-term. On the short-term, a hydrogen system will therewith be a system that is dependent on the cleaning of natural gas through steam methane reformation. The realization of a hydrogen provision to the residential and service sector will hence contribute to the CO<sub>2</sub> policy goals but not to the reduction of the dependency on natural gas. Such a hydrogen gas system will unavoidably be subject to stricter regulations since the market will not determine how hydrogen will be provided. On the longer-term, renewable electricity generation technologies have the potential to fully replace natural gas as the energy input to produce hydrogen. The latter requires enormous amounts of cost-attractive and available green electricity production capacities. The development of these capacities is time-consuming, and the pace is highly unsure. The successful integration of hydrogen in the Dutch gas infrastructure for the provision of hydrogen to the residential and service sector is technically possible, but on the short-term dependent on the developments in the laws and regulations regarding the provision of hydrogen, the CO<sub>2</sub> emissions and price, and the price development of electrolysis.

The main research question of the thesis project is, *how to successfully integrate hydrogen into the current natural gas infrastructure and guarantee the adequate provision of energy to the Dutch residential and service sector?*

The answer to this question is that hydrogen can successfully be integrated when the current gas laws and regulations are adjusted, the energy markets accurately reflect the costs of CO<sub>2</sub>, and hydrogen gas is adopted as the gas standard for the Dutch gas distribution grids. A transition to hydrogen is hence technically possible but requires enormous up-front investments and a clear direction in the future of the Dutch gas infrastructure. The laws and regulations of the hydrogen provision and the organization of the transformation of the existing natural gas grid to a hydrogen grid, are essential regarding the need for enough hydrogen supply and demand and the need to safeguard the energy security in the Netherlands. The Dutch distribution grids and the end-use equipment in the buildings will need to be compatible with hydrogen. These adjustments imply an enormous organizational challenge that includes a variety of public and private actors. It is therefore impossible to realize the provision of hydrogen to the Dutch residential and service sector without strict regulations and direction from the government and the public system operators. Without clear regulations on the short-term, it will be unlikely that a hydrogen system will emerge that can compete with natural gas and the grey alternatives to natural gas.

## 7.8 Policy Recommendations

To successfully integrate hydrogen, a couple of key decisions need to be made regarding the potential future of a hydrogen infrastructure. The technical system design challenges of the integration of hydrogen are not the main bottlenecks. The integration will largely be dependent on the ability of green hydrogen production technologies to become cost-efficient and the acceptability of blue hydrogen production technologies. The uncertainty that exists in the future path of the natural gas infrastructure and the role of hydrogen does not enhance the successful integration of hydrogen. Important bottlenecks for the integration of hydrogen that need to be addressed are:

1. The uncertainty of the role of hydrogen in the gas provision and hence in our future energy provision.
2. The unaddressed potential benefits of integrated energy systems in terms of the technical transmission and distribution activities and in terms of their markets.
3. The specific regulatory elaboration of the CO<sub>2</sub> goals regarding the Dutch energy systems and hence regarding the energy tariff structures.
4. The uncertainty in the role of blue hydrogen and blue electricity production in the provision of energy.
5. The current market model and the limited role of the public system operators in terms of the development of a hydrogen system and hence the development of hydrogen supply and demand.
6. The degradation of the energy buffer capacity of the current gas infrastructure and hence the decrease in energy security.
7. The degree of vertical and horizontal integration of the system operators in the execution of the regional energy strategies.
8. The taxation of the production of hydrogen and moreover, the taxation of grey hydrogen in combination with grey electricity and heat.

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## 9. Appendix – Expert interviewing

This appendix elaborates on the interview outline in section 9.1 and on the summaries of the semi-interviews in combination with their interpretations in section 9.2 to 9.8. Seven interviews are conducted with experts in the field of natural gas and hydrogen. The experts that are interviewed are:

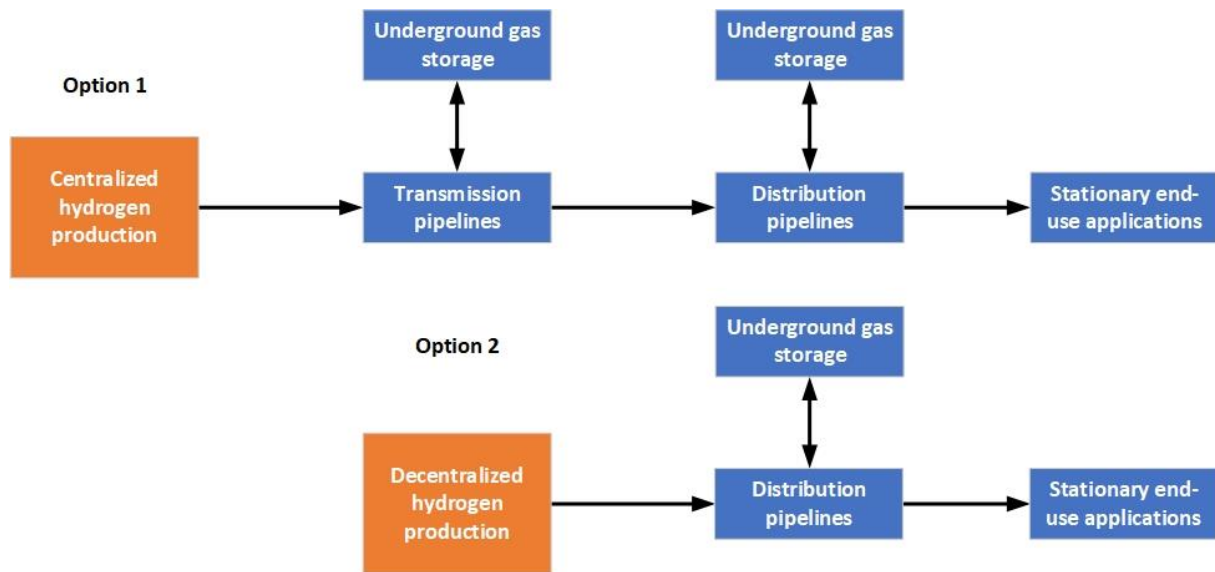
1. Prof.dr. A.J.M. van Wijk – Full professor at TU Delft, Future Energy Systems
2. Dr. A.F. Correljé – Research fellow at TU Delft
3. Ir. C. Hellinga – Scientific advisor Delft Energy Initiative
4. E. Huijzer – Grid strategist at Liander
5. P. te Morsche – Senior policy advisor gas at Liander asset management
6. Dr. T.W. Fens – Associate Partner at Deloitte B.V. and senior research fellow at TU Delft
7. Prof.dr.ir. Z. Lukszo – Full professor at TU Delft, Engineering Systems and Services

Interviewing, as a research method, refers to the collection of knowledge by asking an interviewee various question. These questions are usually asked to several interviewees for the purpose of collecting the empirical data that is needed. The questions can be asked in a standardized or non-standardized sequence and can have a varying or fixed content regarding the various interviews that are conducted. The thesis project will apply interviewing as a method to obtain knowledge about the implications of integrating hydrogen. Moreover, interviewing will be used to validate the results obtained from the application of the comprehensive design framework. The interviewing method conducted in the thesis project is referred to as semi-structured interviewing. Semi-structured interviews contain both open and closed questions with a non-standardized sequence but with a consistent content over the several interviews (Gudkova, 2018). The latter is important to gain adequate and valid knowledge about the content of the interviews (Gudkova, 2018).

Since the application of the framework is rather untested and open to errors of the specific interpretation of the researcher, the thesis project uses semi-structured interviewing as a method to iterate and validate the application of the comprehensive design framework. Interviews hence consists of questions that are aimed to test the results obtained by the application of the framework and to add useful overlooked insights to these results. Semi-structured interviewing is therewith used as a supportive research method to answer sub research question 4, sub research question 5, and sub research question 6. The focus of the semi-structured interviews is to obtain insights in the potential changes and design challenges that an integration of hydrogen poses.

## 9.1 Interview outline

**Step 1:** Introduction to hydrogen infrastructure options with considerations about design.



**Design options within hydrogen infrastructure options:**

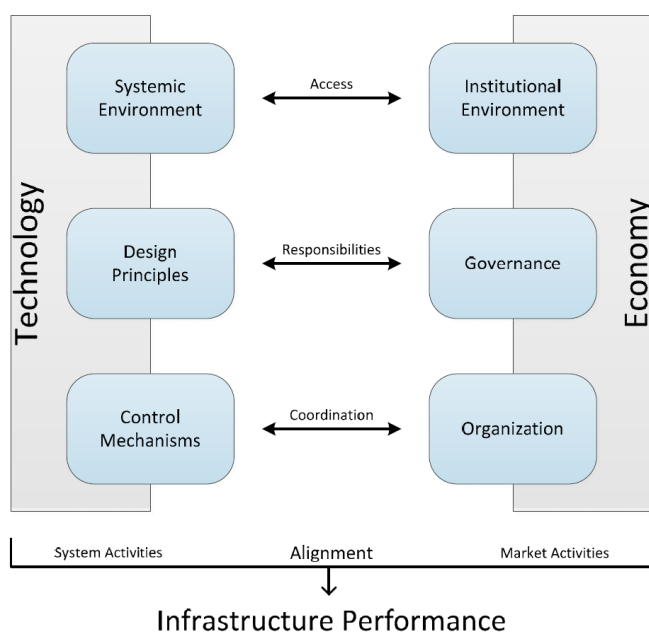
**Option 1:** is the gas transmission infrastructure totally transitioned to the hydrogen infrastructure?

**Option 2:** will the network topology of the distribution grid be centralized (i.e. in which the gas flow is connected to centralized hubs of production) or decentralized (i.e. in which the gas flow is connected to several decentralized production units).

**OPEN QUESTION:** What changes with the integration of hydrogen? Who should participate, where?

**Step 2:** Introduction framework

Study aims at investigating how the integration of the above options affects the technical-operational and economic-institutional functioning of the system.



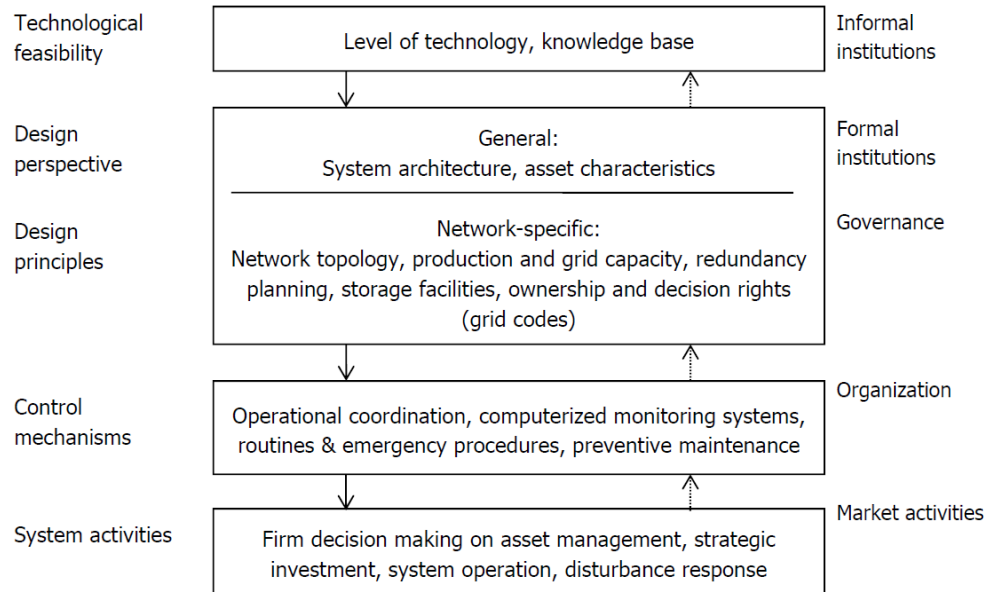
**Access:** about the generic design of energy infrastructures.

**Responsibilities:** about the allocation of the roles and responsibilities of the actors regarding operational and market activities.

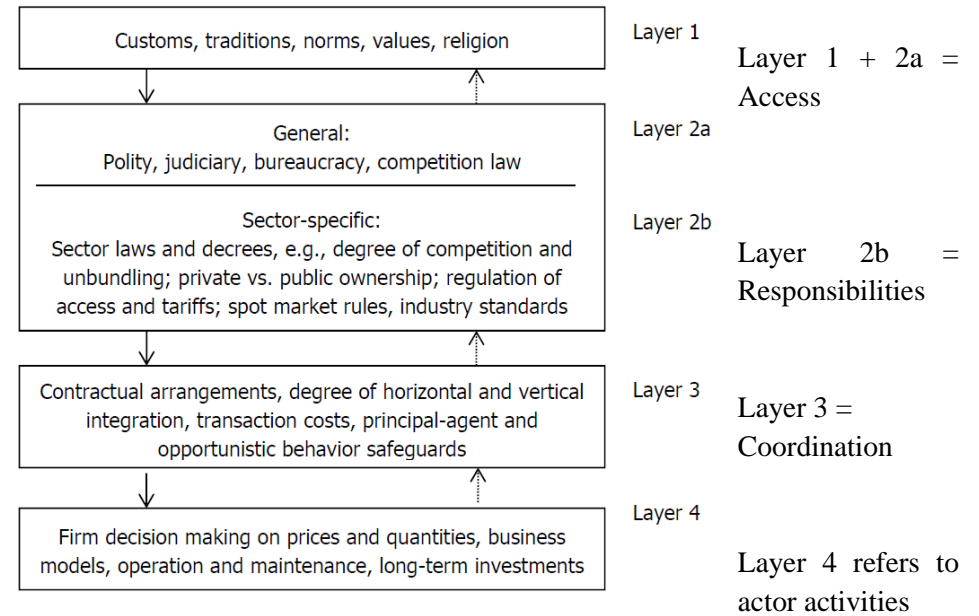
**Coordination:** About the technical control mechanisms and the modes of organization that structure the operational system and market activities.

**Alignment:** certain degree of alignment must exist for the infrastructure to function technically reliable, economic efficient, and socially desired.

### Technical-operational system design



### Economic-institutional system design



Possible explanation:

### **Step 3: Questions specific per layer and dimension**

Per question option 1 and option 2 will be discussed.

#### **Technical-operational**

##### **Access (allowed to participate in)**

##### **System architecture**

1. What changes in the overall shape of the system, its attributes, and how the attributes interact?
2. Is this challenging/problematic?

##### **Asset characteristics**

3. How do the asset characteristics change, what is fundamentally different?
  - a. Production
  - b. Transmission
  - c. Distribution
  - d. Storage
  - e. End-use
4. How is this challenging/problematic?

##### **Responsibilities (control and intervention tasks)**

##### **Network topology**

5. How should the network topology change because of the integration of option 1 and option 2?
6. How is this challenging/problematic?

##### **Production, storage, and grid capacity**

7. How does the production capacity changes?
8. How does the storage capacity changes?
9. How does the grid capacity changes?
10. How are these changes challenging/problematic?

##### **Redundancy planning**

11. Are extra redundancy measures necessary compared to natural gas?
12. Are these challenging/problematic?

##### **Ownership and decision rights**

13. Who should get the ownership and decision rights of?
  - a. Production facilities (option 1 and option 2)
  - b. Storage facilities
  - c. End-use applications
14. How is this different than with natural gas?
15. How is this challenging/problematic?

##### **Coordination (centralized vs decentralized)**

##### **Operational coordination**

16. How should the operational coordination of .... be changed?
  - a. Production
  - b. Transmission
  - c. Storage
  - d. Distribution
  - e. End-use
17. How is this challenging/problematic?



### **Routines, emergency procedures, and preventive maintenance**

18. How should the routines, emergency procedures, and preventive maintenance activities change?
19. Is this challenging/problematic?

### **Economic institutional**

#### **Access (state vs market)**

#### **Competition**

1. To what degree should competition be allowed?
  - a. Production
  - b. Distribution
  - c. Storage
  - d. Transmission
  - e. Wholesale
  - f. Retail
2. How is this different to the current situation?
3. How is this challenging/problematic?
  
4. To what degree should government intervention be allowed?
  - a. Production
  - b. Distribution
  - c. Storage
  - d. Transmission
  - e. Wholesale
  - f. Retail
5. How is this different to the current situation?
6. How is this challenging/problematic?

### **Responsibilities (ownership and decision rights)**

#### **Access regulation**

1. How should access to be regulated?
  - a. Production
  - b. Distribution
  - c. Storage
  - d. Transmission
  - e. Wholesale
  - f. Retail
2. How is this different to the current situation?
3. How is this challenging/problematic?

### **Cost and tariff structure**

4. How does the cost-structure change?
5. What should be the tariff structure of hydrogen (fixed, market)?
  - a. Wholesale level
  - b. Retail level
6. How should this be regulated?
7. What should be the tariff-structure of hydrogen capacity?
  - a. Transmission
  - b. Distribution
8. How is this different from natural gas?
9. How is this challenging/problematic?

### **Ownership and decision rights**

10. Who (public vs private) should get the ownership and decision rights (property rights: right to use, right to own, right to sell, right to own the benefits) on:
  - a. Production
  - b. Transmission
  - c. Storage
  - d. Distribution
  - e. Wholesale market
  - f. Retail market
  - g. End-use applications
11. How is this challenging/problematic?

#### **Spot market rules**

12. Do the spot market rules need to change and how?
13. Is this challenging/ problematic?

#### **Industry standards**

14. How should the industry standards change?
15. Is this challenging/problematic?

#### **Coordination (Vertically integrated vs market)**

##### **Contractual arrangements and modes of organization**

16. How should the volumes of hydrogen be transacted among parties?
17. How should storage service be transacted among parties?
18. How should capacity allocation be organized?
19. How should capacity utilization be organized?
20. How should the production, storage, and transportation capacity adequacy be safeguarded?
21. How is this challenging/problematic?

#### **Degree of horizontal and vertical integration**

22. How should horizontal and vertical integration be organized?
23. How is this challenging/problematic?

## 9.2 Summary of the interviews

This section will present the main findings of the semi-structured interviews. These findings are used in the identification of the changes that an integration of hydrogen pose and the related design challenges for a hydrogen gas infrastructure.

### **Interview Prof.dr. A.J.M. van Wijk – Full professor at TU Delft, Future Energy Systems**

Hydrogen will be predominantly produced centrally in large volumes that will be injected in the existing transmission grids. The production of blue hydrogen will be unavoidable and hence CCS will be unavoidable on the short-term. With the proven hydrogen technologies available, the main challenge is in the organization of the transition to hydrogen and the formulation of the laws and regulations. The transition to hydrogen requires direction of the government and organization in the realization of hydrogen production capacity, the adjustments in the grid, and the end-use equipment. The formulation of laws and regulations regarding the provision of hydrogen is essential for a hydrogen system to emerge and will be a time-consuming activity. There is no need to infringe with the consumer sovereignty.

### **Interview Dr. A.F. Correljé – Research fellow at TU Delft**

An extensive hydrogen infrastructure will not emerge on the short-term within the current market design. The capital-cost intensive hydrogen infrastructure will hence be dependent on bilateral agreements to ensure the return on investments. The absence of a political choice and clear laws and regulations result in an unsure investment climate and hence an unsure future for hydrogen gas. The emergence of a hydrogen infrastructure on the short-term will therefore be largely dependent on the role of the government. A more intensive regulatory and directive role of the government in combination with the absence of a well-functioning market, is likely to result in a more regulated and integrated system with less consumer sovereignty.

### **Interview Ir. C. Hellinga – Scientific advisor Delft Energy Initiative**

The role of gas in the provision of heat to the built environment will stay relevant due to the convenience of its application and the inability to earn back all-electric investments due to the minor differences between the electricity and gas prices. The transition to hydrogen gas is an enormous organizational and regulatory challenge but includes relatively low transition costs. The centralized production of hydrogen in large volumes will be the only cost-effective option on the short-term and will be dominantly dependent on SMR with CCS integrated. The production of green hydrogen becomes more cost-competitive over time. The hydrogen infrastructure will be, in analogy with the natural gas infrastructure, divided in hydrogen with two different gas quality standards.

### **Interview E. Huijzer – Grid strategist at Liander**

The regional energy strategies do not allow the individual consumer to choose their alternative to natural gas anymore. These strategies hence make an integrated energy system perspective, on the distribution level, more convenient in terms of total system cost efficiencies. The production of hydrogen will be conducted centralized in large volumes. The production of green hydrogen in the Netherlands will be dominantly dependent on the availability of wind energy and the production of blue hydrogen on the availability of natural gas. Hydrogen condensing boilers will be the main end-use equipment that will be used due to their relatively low investment cost and the marginal change in the user interface and heating systems. The degree to which hydrogen will be injected in the lower-pressure grids will determine the complexity of the grid operations and the way in which the existing natural gas grid needs to be adjusted. Long-term contracts are needed for the security of the investments and will be difficult to establish in the built environment. The hydrogen gas grid will be coupled to the electricity grid to

accommodate the volatile nature of the renewable energy sources. No level playing field for hydrogen can be defined yet, since no hydrogen infrastructure exists, and an inadequate level playing field could result in undesirable lock-in effects. Hydrogen in the built environment will logically be used when the hydrogen infrastructure is more mature and other end-use sectors as the industry and the mobility sector are already using hydrogen.

**Interview Pascal te Morsche – Senior policy advisor gas at Liander asset management**

The market price for hydrogen will determine how the supply of hydrogen will emerge and determine how the gas will be buffered and hence how it will flow through the transmission and distribution grids. The production of large volumes of gas at the distribution level determine whether the gas needs to flow bidirectional. The public transmission and distribution operators need to be allowed to develop and exploit hydrogen infrastructure and the gas qualities in which the hydrogen will be provided need to be established. Higher pressure gas networks include higher injection capacities than lower pressure networks. The location of the hydrogen production facilities and the possibilities of a grid connection are hence determined by the capacity of the grid and the possibilities to be connected. The realization of a hydrogen infrastructure includes path-dependencies in the development of supply, demand, transportation capacity, and buffer capacity. Production capacity will be dominantly based on SMR capacity with CCS integrated. This is necessary because the largest organizational challenge of a transition to hydrogen is to install and connect the new end-use equipment in the built environment. From a total system perspective, it is inefficient to give the individual end-user a choice in the energy carriers that are distributed to specific areas.

**Interview Dr. T.W. Fens – Partner at Deloitte B.V. and senior research fellow at TU Delft**

The production of hydrogen will get a centralized character due to the large volumes that are needed. The production of green hydrogen will be dependent on the surplus of renewable electricity and the production of blue hydrogen will play a key role in the transition towards the development of enough green hydrogen supply. Blue hydrogen is hence needed to already start the development of the hydrogen infrastructure. The decentralized production of hydrogen will also play a key role in the storage of the local renewable energy surplus. The challenge of a transition from natural gas to hydrogen gas is one of costs and manageability, not a technical one. A hydrogen system will evolve gradually where it is cost-efficient, publicly accepted, and fits in the institutional environment. Fuel cell end-use systems in the built environment can help the transition since they are able to function both with natural gas and hydrogen gas. The need for hydrogen gas in the built environment is high in terms of the CO<sub>2</sub> reduction goals. Short-term storage capacity in the built environment is likely to be organized more locally. The transactions of hydrogen can occur in the existing gas market, only the transactions of hydrogen conversion capacities are new.

**Interview Prof.dr.ir. Z. Lukszo – Full professor at TU Delft, Engineering Systems and Services**

The production of hydrogen should be based on electrolysis both centralized and decentralized. The price and availability of green hydrogen production and import capacity hence determines the viability to use hydrogen. The coordination between the decentralized and centralized production (and imports) of hydrogen is essential both technically and organizationally. When the local supply of gas emerges in large volumes, it is important that the supply can be traded in a market and that both the retail and the wholesale market function well-together. Tariff regulations are essential to secure the investments in the hydrogen infrastructure and hence essential in the realization of enough supply and demand. Transmission and distribution activities need to stay publicly owned and operated, the latter activities should be privately conducted, and hydrogen should be transacted in a market.

### 9.3 Interview Prof.dr. A.J.M. van Wijk – Full professor at TU Delft, Future Energy Systems

Date: 26/02/2019

#### Summary of interview

##### **Decentralized production of hydrogen**

- The decentralized production of hydrogen is like the production of green gas in terms of the injection in the distribution grids.
- The volumes of hydrogen that can be produced on a decentral level are marginally compared to the possibilities of a centralized production. The distribution of the centralized and decentralized production of hydrogen will hence be like the current distribution of the supply. The large part is produced central by the extraction of natural gas and a small part is produced locally from biogas. The decentralized production of hydrogen is therewith in volume not comparable with the centralized production of hydrogen.
- The decentralized production of hydrogen will largely be based on the renewable electricity surplus and will hence be a measure to prevent large-scale investments in the electricity grid.

##### **System architecture**

- The system architecture of a hydrogen infrastructure will be like the current natural gas system architecture.
- The storage of hydrogen will be organized centrally. The surplus of the decentralized hydrogen production will hence be transported to the transmission grid and from there to the storage facilities. For the bidirectional flow of gas compression stations are necessary.
- The system will be organized centrally, the decentral production of hydrogen will not occur on a large-scale.
- The obligation to connect the hydrogen producers and consumers to the public grids will still exist.

##### **Volatile supply profile**

- The supply profile of green hydrogen will be more volatile due to the volatile nature of the renewable electricity generation.

##### **Challenges in the organization of the transition and the adjustment of the laws and regulations**

- The organization of the transition is essential. It is an enormous operation to realize the production capacity, to adjust the natural gas grids, and to replace the end-use equipment.
- The Dutch Gas Act is currently not applicable to hydrogen. Hydrogen related activities are currently prohibited for the system operators to participate in.
- Hydrogen gas standards need to be formulated.
- Laws and regulations regarding the safety of the design and the operations need to be formulated.

##### **Technological changes**

- The infrastructure needs to be adjusted to be compatible with hydrogen. These challenges are less an issue than the organizational and regulatory issues.
- The technology is already available. The pilot projects imply that the technology is not yet available but that is not the case. These projects are experimental projects because the current laws and regulations do not allow hydrogen to be transported to the existing infrastructure. Privately owned and operated pipeline networks that transport hydrogen do already exist for over 40 years.

## **Production of hydrogen**

- The production of hydrogen is a conversion process. This could be compared with the conversion from high-caloric gas to low-caloric gas by the blending with nitrogen. From this perspective it could be argued that hydrogen conversion can be organized in the same way as the conversion of natural gas (i.e. in a way that the system operators are offering a conversion service next to the transportation service).
- It is a fundamental difference in terms of the laws and regulations whether the production/ conversion of hydrogen is categorized as a production process or as a conversion process.
- If hydrogen is categorized as a production process, taxes apply to the production of electricity and to the production of hydrogen. In this way the production of hydrogen becomes costly.
- It is important that laws and regulation determine which parties (public or private) can participate in the hydrogen production activities.
- The organization of the production of hydrogen in the laws and regulations is a bottleneck. The government needs to take control in this process and needs to formulate laws and regulations that are applicable to the provision of hydrogen.
- The availability of green energy production capacity on the short-term from will be insufficient to satisfy the demand for energy. CCS will be necessary to decarbonize the electricity and gas supply.

## **Fundamental choices in laws and regulations**

- Fundamental choices need to be formulated by the government in the laws and regulations regarding a hydrogen infrastructure and the transition.
- The market design needs to be defined and it needs to be defined which parts will be transformed in which sequence.
- The government needs to determine whether the costs of the investments in hydrogen need to be socialized over the total volume of natural gas and hydrogen gas.

## **The end user determines the connection**

- The end user determines which green energy carrier it will use. A connection obligation to the public grids will still exist and will hence allow the consumer to choose between different alternatives.

## **Changes positioned within Comprehensive Design Framework**

### **Changes in the technical-operational dimension**

#### **Access**

#### **System architecture**

- The flow from the distribution to the transmission grids need to be facilitated by boosters.
- No large-scale production will occur locally.

#### **Asset characteristics**

- New production/ conversion technologies need to be installed.
- The gas grid and the installations used for the transmission and distribution need to be adjusted to be compatible with hydrogen.
- End-use equipment needs to be replaced.

#### **Responsibilities**

#### **Network topology**

- A new production/ conversion segment enters the supply chain of the gas infrastructure.
- CCS infrastructure will be necessary to produce blue hydrogen.

## **Production, grid, and storage capacity**

1. The production of green hydrogen will be more volatile due to the volatile nature of the renewable energy technologies.
2. The production of blue hydrogen will be essential in the start of the transition towards a hydrogen infrastructure.

### **Redundancy planning**

-

### **Ownership and decision rights**

3. Ownership and decision rights regarding the design and operations of the various production, transportation, storage, and end-use assets need to be defined.

### **Coordination**

#### **Operational coordination**

4. Safety instructions need to be formulated for the operation of a hydrogen infrastructure.

### **Routines, emergency procedures, and preventive maintenance**

-

### **Changes in the economic-institutional dimension**

#### **Access**

#### **Competition and state intervention**

5. The production of hydrogen is a fundamentally different process compared to the production of natural gas.
6. The government should take a leading role by the formulation of hydrogen laws and regulations.
7. Consumer sovereignty must be safeguarded.

### **Responsibilities**

#### **Access regulation**

8. The public system operators are currently not allowed to participate in any activity related to hydrogen. The Gas Act and energy codes do not address the use of hydrogen.

### **Tariff regulation**

-

### **Ownership and decision rights**

9. Property rights regarding the transaction of the volumes of hydrogen, and the transport, storage, and conversion services need to be defined. It needs to be determined which entities (public or private) can participate in the hydrogen production activities.
- 10.

### **market rules**

1. The market for hydrogen needs to be defined.

### **Industry standards**

11. Hydrogen gas quality standards need to be formulated.

## Coordination

### Contractual arrangements and modes of organization

12. The costs for the investment in hydrogen needs to be accommodated in an adequate regulatory framework.

### Horizontal and vertical integration

-

### Principal-agent and opportunistic behavior safeguards

-

What challenges are there?

	<b>Technical-operational</b>	<b>Economic-institutional</b>
<b>Access</b>	<ol style="list-style-type: none"><li>1. New hydrogen production assets.</li><li>2. Adjustment of existing transmission, storage, distribution, and end-use assets.</li></ol>	<ol style="list-style-type: none"><li>1. The production of hydrogen gas is a conversion process.</li><li>2. Direction of the government.</li><li>3. Consumer sovereignty.</li></ol>
<b>Responsibilities</b>	<ol style="list-style-type: none"><li>1. New production/conversion segment of gas enters the supply chain.</li><li>2. CCS needs to be integrated in the infrastructure.</li><li>3. The production of green hydrogen will be more volatile.</li><li>4. Ownership and decision rights regarding production facilities.</li></ol>	<ol style="list-style-type: none"><li>1. Access to hydrogen transmission and distribution activities.</li><li>2. Market design.</li><li>3. Hydrogen gas quality standards.</li></ol>
<b>Coordination</b>	<ol style="list-style-type: none"><li>1. Formulation of safety instructions.</li></ol>	<ol style="list-style-type: none"><li>1. Investments need to be accommodated by regulatory framework.</li></ol>

### Explanation of the challenges

#### Access – Technical operational

1. The production of hydrogen is a conversion process that can be conducted using various sources of energy. The production segment of hydrogen will hence interact with a variety of systems for the provision of the energy input. The challenge is to integrate the hydrogen production segment in the current Dutch gas system architecture in a cost-efficient way.
2. The current assets in the transmission, storage, distribution, and end-use segments are compatible and fine-tuned on the utilization of natural gas. The latter assets need to be partly adjusted or replaced to utilize hydrogen.
3. A new gas production segment enters the system architecture of the gas infrastructure and new assets are needed in the supply chain. The challenge is to determine what assets should make up the technologies of the hydrogen system.

#### Responsibilities – Technical operational

1. A new gas production segment enters the network topology of the gas infrastructure. The challenge is to determine where the production facilities should be sited and how they should interact with the current gas infrastructure.



2. CCS infrastructure needs to be integrated in the blue hydrogen production facilities. The challenge is to determine how the delineation of the CCS activities and production activities will be defined.
3. The production of green hydrogen will be more volatile since it will rely on the availability of renewable electricity surplus. The challenge is to design a hydrogen system that adequately matches supply and demand under the volatile nature of the production of green hydrogen.
4. Ownership and decision rights for the various production facilities need to be defined. The challenge is to determine which entities (public or private) can own and operate the various production assets.

#### **Coordination – Technical operational**

1. Safety instructions for the operation of a hydrogen infrastructure need to be defined, just as with the utilization of natural gas and biogas. The challenge is to determine whether the current safety instructions are applicable to hydrogen and where the safety instructions need to be renewed.

#### **Access – Economic-institutional**

1. The production of hydrogen gas is a conversion process. The laws and regulations applicable to the production of hydrogen should address these characteristics. The challenge for the government is to determine how the production of hydrogen will be categorized in the laws and regulations. The latter is more difficult since hydrogen conversion can be conducted in several ways including a variety of processes on different scales.
2. Large-scale investments are needed to realize a hydrogen infrastructure. The government should have a leading role in incentivizing these investments. The challenge for the government is to determine which role hydrogen will play on the short-term. Laws and regulations need to address the role. Important here are the goals that the energy systems need to address. The latter is hence strongly a political issue.
3. Consumer sovereignty should be safeguarded. With a strong role of the government, the latter can potentially be hard to achieve. Especially looking at a total system efficiency perspective. The challenge for the government is to determine to what degree the consumer sovereignty should be safeguarded.

#### **Responsibilities – Economic-institutional**

1. The TSO and DSOs are not allowed by the current laws and regulations to participate in any activities related to hydrogen. Moreover, they are not allowed to be involved in other activities that the transmission and distribution of natural gas. The challenge is to change the laws and regulations to allow for the transmission and distribution of hydrogen. Moreover, a challenge is to determine if and under what conditions the TSO and DSOs can participate in other activities than the transmission and distribution of gas.
2. The total market design including the tariff structure and the access regulations of the various entities needs to be defined by the government. Such a market design should include a mechanism to incentivize the large-scale investments. The challenge for the government is to determine which market design is adequate and hence to prevent undesirable lock-ins from occurring.
3. Hydrogen gas quality standards for the various transmission and distribution networks need to be formulated and stated in the Dutch laws and regulations. The challenge is to formulate adequate standards and to adjust the Gas Act, the Regulation on the Gas Quality, and the energy codes.

#### **Coordination – Economic-institutional**

1. Proper modes of organization need to be in place to provide safety mechanisms for the investment in the hydrogen technologies. The challenge is to determine which modes of organization are appropriate and to hence prevent undesirable lock-ins.

## 9.4 Interview Dr. A.F. Correljé – Research fellow at TU Delft

Date: 26/02/2019

### Summary of interview

#### Hydrogen system

- The organization of the techno-operational and the economic-institutional environments start at an abstract level.

#### A key issue in the price

- What determines the price of hydrogen? The current natural gas prices are for example not based on the production costs. These prices are the outcome of the natural gas transactions. The spot market does not reflect the marginal costs, the price is an outcome of the demand and supply for natural gas.
- The price structure determines whether investments will be made by private companies and how different players in a hydrogen market can gain profits. Moreover, the price structure determines how certain risks are allocated.
- The price structure determines to a large extent how the roles and responsibilities will be allocated in a hydrogen infrastructure.

#### Fundamental choices

- The access layer of the comprehensive design framework includes the fundamental choices that need to be formulated. These choices determine to a large extent how the system will be designed.

#### Centralized production of hydrogen

- The market for the industry is an international market.

#### Start of a hydrogen system

- Number of producers and consumers will be small.
- Bilateral contracts will be needed since there will not be enough participants for a market.
- Increasing numbers of producers and consumers will eventually allow a market to exist.
- The economic risks need to be accommodated by a proper institutional framework.

#### Formulation of laws and regulations regarding the provision of hydrogen

- The system of laws and regulations can be adjusted gradually.
- A trade-off exists to which degree the government should define the level playing field of the actors.

#### The convergence of the substitutes for natural gas-based heating

- All-electric and district heating are also, next to hydrogen, alternatives to natural gas for the heat supply of the built environment. How are these price structures defined?
- A fundamental choice is whether the prices of the different alternatives will differ. Cooking and heating services can for example be priced instead of the energy carrier. Also, the energy content can have a price instead of the volumes of gas.

#### Freedom to choose a retail supplier (i.e. consumer sovereignty)

- Will the freedom to choose a retail supplier still exist in a hydrogen market?
- An energy system that is focused on system wide efficiency and a universal energy price would imply that the consumers in the built environment cannot choose.
- The latter developments are comparable to the current developments of the regional energy strategies in which municipalities determine a proper alternative to natural gas.

- These developments could lead to a more vertically integrated role of a public entity in the provision of energy to the built environment. Such a model is comparable to the Dutch water management model or a public utility model.
- Costs are hence socialized over all the connections and decision rights are democratically owned by means of an elected board.
- The energy supplier model is basically established to enhance the competitiveness of the market to facilitate more efficiency in terms of energy and cost efficiencies and to safeguard the customer sovereignty.
- The drawback of the latter model is that it is hard to ensure the system wide efficiencies and to safeguard the protection from externalities such as CO<sub>2</sub> emissions.

### **Bottlenecks in European laws and regulations**

- System operators are not allowed to participate in hydrogen activities.
- The electricity and gas laws and regulations are separate institutional systems.
- Current developments in the European Union do address the transition towards a more integrated energy system.

### **Political choice**

- How the hydrogen system will emerge is strongly determined by political choice.
- Where environmental goals will support a more drastic and quick transition. Economic goals could prefer a wait-and-see approach. The former implies a more significant role for the government intervention than the latter.

### **Energy strategies**

- Energy strategies imply a significant role for the distribution system operators, which are currently legally constrained to participate in other activities not related to the distribution of electricity and natural gas.

### **Shift from operational cost perspective to capital cost perspective**

- Compared to the natural gas system, hydrogen systems will be capital cost intensive instead of operational cost intensive due to the large investments needed.
- The latter could imply that the provision of hydrogen will be organized more in the form of a subscription. Market prices will not determine the price of hydrogen, but the prices will be regulated. The prices of the transport services and the volumes will reflect the capital and operational costs.
- Hydrogen production activities are largely based on joint costs structures due to the nature of the process. It is hence hard to determine the production costs of hydrogen and therewith base the price structure of hydrogen of the costs.
- Prices can be regulated in a way that the most expensive production technology that is desirable (i.e. socially preferred) can be played off. Such a model will enhance the emergence of cheaper production technologies.

### **Competition in a more vertically integrated system**

- Regions can organize tenders for both the design and construction, and the operation of the various systems.

### **Challenge of phasing out the natural gas infrastructure**

- Currently, the number of market players in the Netherlands declines due to the large uncertainty in the Dutch natural gas sector.

- Natural gas producers are not investing anymore in the Dutch natural gas sector due to the uncertain political climate.
- A limited number of large producers such as NUON, Essent, Eneco, et cetera, are already started with the transition away from the production of natural gas. These producers are also subject to the large uncertainty of how the future energy system will look like.

### **Costs of energy**

- Energy costs will increase. This is an important institution.

## **Changes positioned within Comprehensive Design Framework**

### **Changes in the technical-operational dimension**

#### **Access**

#### **System architecture**

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#### **Asset characteristics**

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#### **Responsibilities**

#### **Network topology**

-

#### **Production, grid, and storage capacity**

-

#### **Redundancy planning**

-

#### **Ownership and decision rights**

-

#### **Coordination**

#### **Operational coordination**

-

#### **Routines, emergency procedures, and preventive maintenance**

-

### **Changes in the economic-institutional dimension**

#### **Access**

#### **Competition and state intervention**

- Long-term bilateral contracts will be needed to let the hydrogen system to emerge.
- The government needs to determine how the level playing field will be determined. More government intervention could be desirable.
- Need to determine if hydrogen is going to compete with alternatives and what tariffs will be applicable. The change is that a hydrogen market will not exist immediately.

- In a transition to a hydrogen infrastructure, consumer sovereignty is hard to safeguard in terms of a free choice in energy carrier. System efficiencies will not cause the most efficient solutions on the individual consumer level.

## **Responsibilities**

### **Access regulation**

- The access regulation needs to enhance the emergences of producers and consumers.
- System operators need to be allowed to participate in hydrogen related activities.
- Distribution system operators are currently not allowed to participate in any activity not related to the distribution of gas. The laws and regulations should change if the role of the DSO is to become more intensive in the facilitation of the regional energy strategies.

### **Tariff regulation**

- Compared to the current natural gas infrastructure, the hydrogen infrastructure will be capital cost intensive instead of operational cost intensive. The latter could change the way in which gas is provided and priced in the built environment.
- The production costs of hydrogen are largely based on joint cost structures which makes it hard to determine the cost price of hydrogen.
- Prices can be regulated in a way that only the desired hydrogen production technologies can emerge.
- Energy costs will increase due to the higher costs of producing green and blue energy.

### **Ownership and decision rights**

- The economic risks of the transition to hydrogen need to be allocated to the various entities in the infrastructure.

### **Spot market rules**

-

### **Industry standards**

-

### **Coordination**

#### **Contractual arrangements and modes of organization**

-

### **Horizontal and vertical integration**

- The integration of hydrogen as an energy carrier requires a more intensive role of the public utilities due to the lack of a market to coordinate the transactions.
- Competition in the gas production segment can be allowed in for example tenders.

### **Principal-agent and opportunistic behavior safeguards**

-

What challenges are there?

	<b>Technical-operational</b>	<b>Economic-institutional</b>
<b>Access</b>	3.	4. Market cannot emerge on the short term.

		<ul style="list-style-type: none"> <li>5. Government needs to determine level playing field.</li> <li>6. Consumer sovereignty.</li> </ul>
<b>Responsibilities</b>	5.	<ul style="list-style-type: none"> <li>4. Hydrogen producers and consumers need to emerge.</li> <li>5. System operators are not allowed to utilize hydrogen.</li> <li>6. DSOs potentially get a more intensive role.</li> <li>7. Capital cost will determine the price structure more dominantly than operational costs.</li> <li>8. Joint cost-structure of hydrogen.</li> <li>9. Energy costs will increase due to the production of green and blue energy.</li> </ul>
<b>Coordination</b>	2.	<ul style="list-style-type: none"> <li>2. Modes of organization to secure economic risks.</li> <li>3. More intensive role of the public utilities due to the lack of a market.</li> </ul>

### **Explanation of the challenges**

#### **Access – Technical operational**

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#### **Responsibilities – Technical operational**

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#### **Coordination – Technical operational**

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#### **Access – Economic-institutional**

1. A hydrogen market cannot emerge on the short-term. The challenge is to determine how much government intervention is necessary to facilitate the emergence of producers and consumers.
2. The level playing field of hydrogen needs to be determined to allow for the utilization of hydrogen. The challenge for the government is to define this level playing field in such a way that undesirable lock-ins are prevented as much as possible.
3. The challenge is to determine the degree of consumer sovereignty.

#### **Responsibilities – Economic-institutional**

1. Hydrogen producers and consumers need to emerge. The latter is only possible under proper investment incentives. The challenge is to formulate access regulation and tariffs structures that address the incentives.
2. The laws and regulations do not allow system operators to utilized hydrogen. The challenge is to change the laws and regulations.
3. DSOs are potentially getting a more intensive role since the large transition to alternatives to natural gas requires an intensive transition. The challenge is to adapt the current laws and regulations to the more intensive role of the DSO.

4. The hydrogen gas infrastructure will get more capital cost driven than the current natural gas infrastructure due to the high-up front costs. The challenge is to determine how to accommodate these large up-front costs.
5. The joint cost structure of hydrogen makes it hard to determine the actual cost prices. A cost-plus structure is hence hard to accomplish. With no extensive market for hydrogen it will be a challenge to determine an adequate hydrogen price.
6. Energy costs in the short-term will unavoidably become higher due to the costs of decarbonizing the energy. The challenge is to allocate the costs and benefits of the system.

#### **Coordination – Economic-institutional**

1. Investments in a hydrogen infrastructure imply economic risks. Modes of organization can coordinate the allocation of these risks in such a way that they are safeguarded. The challenge is to determine which modes of organization are appropriate and which modes of organization do not imply undesirable lock-in effects.
2. Since there will not be an extensive hydrogen market on the short-term it needs to be determined whether public utilities need to vertically integrate the various activities in the supply chain. The challenge is to determine if a more intensive role of the public utilities is desirable.

### **9.5 Interview Ir. C. Hellinga – Scientific advisor Delft Energy Initiative**

Date: 19/02/2019

#### **Summary of interview**

##### **Costs of adjusting the Dutch gas grid to a hydrogen grid**

- The costs of adjusting the Dutch gas grid to be compatible with hydrogen are, according the KIWA report, approximately 700 million euros, which is 100 euro per household (Hermkens et al., 2018). With a life span of 50 years this would imply that the annual costs of a national hydrogen grid are approximately 4 euros per year (i.e. including interest).

##### **Transition from a natural gas grid to a hydrogen grid**

- An enormous organizational challenge but the transition includes significantly low transition costs.
- The exact organization of a national hydrogen infrastructure needs to be formulated.
- The offshore oil and gas platforms in combination with the existing pipeline networks can be used to transport hydrogen from offshore production facilities to the shore.

##### **Energy labels**

- Energy labels are not adequate when energy savings are calculated. Empirically, F-labels are for example resulting in less energy savings than theoretically achievable.
- From energy label D and lower (i.e. label E, label F, and label G), the energy consumption per square meter in the buildings stays more or less equal.
- The payback time of the insulation measures for higher energy labels are hence higher than calculated.

##### **Electric heat pumps**

- With the effect of the overestimated energy savings of insulation measures due to the energy labels of the buildings, heat pumps are not a cost-effective option anymore. In the model of CE Delft, it is estimated that heat pumps will annually generate 3 PJ of heat instead of 87 PJ of heat in 2050 due to the above-mentioned effect.

### **Investment costs for hydrogen connection in houses (based on Leeds project)**

- Investment costs for the hydrogen equipment in houses will be approximately € 3500. These investment costs are for the replacement of the gas metering installation, the natural gas condensing boiler, and the natural gas stove.

### **Prices for natural gas, biogas, hydrogen gas in CEGOIA model CE Delft**

- Natural gas prices are currently € 0.25 to € 0.30 per m<sup>3</sup>, which is approximately 2.6 to 3.1 eurocents per kWh<sup>14</sup>.
- Biogas is available for approximately € 0.75 per m<sup>3</sup>, which is approximately 7.7 eurocents per kWh<sup>15</sup>.
- The blue hydrogen production costs are approximately € 1.6 to € 2 per kg, which is approximately 4.8 to 6.0 eurocents per kWh<sup>16</sup>.
- The green hydrogen production costs are approximately € 4 to € 5 per kg, which is approximately 12 to 15 eurocents per kWh<sup>17</sup>.

### **Long-term perspective on hydrogen production**

- Hydrogen will predominantly be produced in a centralized fashion.
- The decentralized production of hydrogen is a problem due to the costs of the decentralized (i.e. small scale) storage options.
- On the short term (i.e. in the transition period to a large share of renewable electricity generation) hydrogen production needs to be based on steam methane reformation of natural gas to satisfy the hydrogen demand. When hydrogen is produced from natural gas, the natural gas dependency will not decline.
- For the longer-term, green hydrogen should be produced.
- Laws and regulations need to be adjusted and constructed to allow the production of hydrogen from several sources.
- Laws and regulations need to be adjusted to allow for CCS.
- Imports of hydrogen from areas in the world with more renewable electricity available will become important. The latter hydrogen will be produced through electrolysis at low electricity costs due to the relatively higher yields from the same installations (i.e. the same investment costs).

### **Underground hydrogen storage options**

- Underground storage of hydrogen in salt caverns is a viable option. Currently the Netherlands has a salt cavern storage capacity of approximately 1/20 of what is needed.
- New salt caverns should be created to overcome the shortage in salt cavern storage capacity. The costs of creating a salt cavern are approximately 1 million euro.

### **Carbon capture and storage (CCS)**

- CCS is likely to be adopted to produce blue hydrogen.
- Operational costs are approximately € 10/ ton CO<sub>2</sub>.
- Carbon capture in steam methane reformation is approximately € 33/ ton CO<sub>2</sub>

### **Network topology**

- The network topology will stay almost the same. Hydrogen is produced centrally, transported through the transmission and distribution pipeline networks, and consumed in the buildings.
- Hydrogen storage is centrally (i.e. on a large-scale) conducted.

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<sup>14</sup> With a calorific value of 35 MJ/m<sup>3</sup>.

<sup>15</sup> Using the same calorific value as natural gas.

<sup>16</sup> With a calorific value of 120 MJ/kg.

<sup>17</sup> Using the same calorific value as blue hydrogen.



- Hydrogen will require two different grids due to the different qualities of hydrogen that need to be transported.

#### **Asset characteristics**

- The reports of DNVGL and Kiwa are a representation of how the asset characteristics in the Dutch natural gas grid should change because of an integration of hydrogen.
- Synthetic seals should be replaced, and compression and metering installations should be adjusted.
- Hydrogen should be odorized.

#### **Safety of hydrogen**

- That hydrogen should be more dangerous than natural gas is an invalid argument looking at the technical characteristics of the hydrogen production, transportation, storage, and consumption.
- The flammability and explosion limits of hydrogen are wider.
- The escape velocity is higher (i.e. hydrogen leakages occur more easily).
- Hydrogen ignites easier than natural gas.

#### **Energy bill**

- The electricity and natural gas prices per kWh are approximately the same. High investment costs of all-electric options are hence hard to cover.

#### **Laws and regulations applicable to hydrogen**

- The whole supply chain of hydrogen requires laws and regulations. This is an enormous challenge.

#### **Hydrogen production is like electricity production**

- Other than with natural gas, hydrogen can be produced at various locations. This makes the production of hydrogen much more comparable with the production of electricity.
- Offshore wind farms produce electricity but also hydrogen.
- More parties can enter the production of hydrogen.
- Hydrogen imports are possible from a variety of countries/ regions/ entities.

#### **Storage of Hydrogen**

- Needs to be regulated due to the safety aspects of the underground storage.
- SodM and EBN can play a key role.

#### **Greenhouses**

- Fuel cells are an economic viable option for the heat demand of the greenhouses.
- In greenhouses, extra insulation is hardly necessary.
- At the level of the greenhouses it could be economically viable to produce hydrogen decentral from wind energy. The largest amount of the electricity produced by the wind mills is directly used in the electric heat pumps.
- Hydrogen is produced to compensate the volatile nature of the wind energy yields. The hydrogen can be stored for periods with higher heat demands.
- Hygro wind mills can produce hydrogen directly for approximately € 2.50 per kg.
- Wind mills will be more beneficial than solar panels looking at the supply and demand profiles of both renewable energy production technologies. With solar panels, the conversion losses of converting electricity to hydrogen will be much higher than with wind mills due to the supply and demand profiles. The hydrogen storage capacity requirement of solar panels will hence be higher.

- The COP of heat pumps in the greenhouse sector is in between 4 and 5. Low hydrogen prices will therefore be necessary for hydrogen to be an economic viable heating option. With the installed wind energy, heat pumps can be used to heat the greenhouses. When the demand for heat is too high, hydrogen can be used from the hydrogen storage to cover the remainder of the heat demand. The hydrogen surplus can for example be used as a fuel for the truck transport in the sector to cover the costs of the hydrogen storage facility.

#### **Technical control mechanisms**

- Technical control mechanisms regarding pressures, gas qualities, temperatures, et cetera need to be adjusted to hydrogen but can be organized in a similar fashion.
- Quality differences in hydrogen will exist in the green and blue hydrogen due to the production technologies.
- Gas standards should be applicable for the various end-use applications.

#### **Competition and government intervention**

- In the production of hydrogen more competition can be allowed due to the nature of the hydrogen production and imports.
- Distribution and transmission grids should be owned and operated publicly to satisfy the public service obligations. Economies of scale are necessary for the system operators to efficiently operate their grids.

#### **Access regulation**

- The hydrogen production should be open to anyone who wants to and is able to produce hydrogen within the laws and regulations applicable.
- Distribution and transmission activities stay publicly owned.
- The decentralized production of hydrogen will require other forms of organization, especially more locally. But the decentralized production is much less likely to occur.
- The decentralized production of hydrogen could occur on-site. For example, for the application in the mobility sector. The latter would require local coordination on the production and distribution of hydrogen. A supervisory body needs to monitor and control this.

#### **Industry standards**

- Industry standards about the gas qualities, operational pressures, asset characteristics, safety requirements and temperatures need to be standardized on a European level.
- The decentralized production of hydrogen can potentially be less dependent on European industry standards. But even with the decentralized production, manufacturers will also contribute to the standardization of technological assets.

## **Elaboration within Comprehensive Design Framework**

### **Changes in the technical-operational dimension**

#### **Access**

#### **System architecture**

- Will remain centralized but include more producers that produce hydrogen from various energy sources compared to the mining companies that extract natural gas.
- Offshore wind farms can produce electricity but also hydrogen. The electricity and hydrogen infrastructure become more intertwined.

#### **Asset characteristics**

- Hydrogen production facilities have other assets characteristics that need to be constructed, operated, and maintained.
- Changes as described in the DNVGL and Kiwa reports.

## **Responsibilities**

### **Network topology**

- The production of offshore hydrogen can utilize the offshore natural gas extraction infrastructure that is already in place. Through electrolysis, wind energy can be converted into hydrogen. The offshore natural gas extraction locations can be used as hydrogen production sites and the connected natural gas pipeline networks can be used to distribute hydrogen to the shore.
- Offshore natural gas fields will no longer be connected to the shore directly if the gas pipeline networks are used to transport hydrogen.
- The underground hydrogen storage will be based on the storage of hydrogen in salt caverns. The predominant part of the salt caverns needed to satisfy the desired storage capacity needs to be created and hence to be sited.
- CCS infrastructure needs to be constructed to produce blue hydrogen. The CO<sub>2</sub> needs to be captured from the hydrogen production process through newly installed equipment and underground CO<sub>2</sub> storage reservoirs need to be developed.
- Hydrogen will require different grids to transport hydrogen from different qualities.
- Hydrogen is a conversion process that is not dependent on a specific geographical location. Production facilities can be sited on a broader variety of locations compared to the production facilities of natural gas.
- Large-scale imports of liquified hydrogen need to be possible.
- The decentralized production in for example the greenhouse sector would change the network topology of the distribution grids if the producers aim to inject the hydrogen in the national grid.

### **Production, grid, and storage capacity**

- Steam methane reformation in combination with CCS (i.e. the production of blue hydrogen) will play a key role in the transition from natural gas to hydrogen. The production of blue hydrogen will be needed since the production capacity of green hydrogen is insufficient and will gradually grow.
- Storage capacity is currently insufficient, but salt caverns can be created.
- The decentralized production on the scale of for example the greenhouse sector could be possible.

### **Redundancy planning**

- Needs to be adjusted to the properties necessary for the reliable and robust functioning of a hydrogen infrastructure.

### **Ownership and decision rights**

-

## **Coordination**

### **Operational coordination**

- Technical control mechanism should be adjusted to the new requirements that hydrogen poses. Gas quality standards need to address the various production and end-use technologies.
- The decentralized production of hydrogen will require extra operational coordination on the local level.

### **Routines, emergency procedures, and preventive maintenance**

- Should be adjusted to the requirements of hydrogen.

### **Changes in the economic-institutional dimension**

#### **Access**

#### **Competition and state intervention**

- The natural gas laws and regulations do not fit the utilization of hydrogen.
- More competition should be introduced in the hydrogen production.

#### **Responsibilities**

#### **Access regulation**

- The access regulation on the production of hydrogen gas does not have to involve a public-private partnership.
- Less regulatory entry barriers should be included in the production of hydrogen.
- The access regulation on the decentralized production of hydrogen needs to be formulated.

#### **Tariff regulation**

- The cost structure of hydrogen will include the investment costs in the production facilities, adjustments to the grid, and the investments in end-use equipment.

#### **Ownership and decision rights**

- Ownership and decision rights regarding the hydrogen production and storage facilities need to be formulated.

#### **Spot market rules**

-

#### **Industry standards**

- Industry standards need to be formed regarding gas qualities, operational pressures, asset characteristics, safety requirements, and temperatures. The standards should preferably be active on a European level.
- The decentralized production of hydrogen can potentially be less dependent on European industry standards.

#### **Coordination**

#### **Contractual arrangements and modes of organization**

-

#### **Horizontal and vertical integration**

-

#### **Principal-agent and opportunistic behavior safeguards**

- Current supervisory bodies need to adapt the production of hydrogen and the storage of hydrogen in their portfolio.

### **What challenges are there?**

	<b>Technical-operational</b>	<b>Economic-institutional</b>
<b>Access</b>	1. More production facilities will produce the supply of hydrogen.	1. Laws and regulations of natural gas do not fit hydrogen.

	<ol style="list-style-type: none"> <li>2. Hydrogen is a conversion process instead of an extraction process.</li> <li>3. Large scale imports of LH<sub>2</sub>.</li> </ol>	<ol style="list-style-type: none"> <li>2. To match production characteristics with degree of competition.</li> </ol>
<b>Responsibilities</b>	<ol style="list-style-type: none"> <li>1. Pipeline networks are compatible with specific gas qualities and characteristics.</li> <li>2. Siting of the storage facilities.</li> <li>3. Siting of the production facilities.</li> <li>4. Coordination between siting process of storage and production facilities.</li> <li>5. CCS infrastructure to produce blue hydrogen.</li> <li>6. To integrate decentralized production.</li> <li>7. Dependence on blue hydrogen production capacity on the short-term.</li> <li>8. Dependency of blue hydrogen on natural gas.</li> </ol>	<ol style="list-style-type: none"> <li>1. Formulation of access regulation for centralized and decentralized hydrogen producers and storage operators.</li> <li>2. Fairness of competition with established/ alternative options.</li> <li>3. Ownership and decision rights are not formulated yet.</li> <li>4. Formulation of industry standards</li> </ol>
<b>Coordination</b>	<ol style="list-style-type: none"> <li>1. Coordination of decentralized production.</li> </ol>	

### Explanation of the challenges

#### Access – Technical operational

1. The transmission grid requires to be connected to a larger number of producers with a variety of production technologies. The technical system architecture needs to be adjusted to be compatible with a larger number of producers with different production patterns.
2. Hydrogen production is a conversion process instead of an extraction process. Hydrogen can hence be produced from a variety of energy sources that need to be available. Natural gas is produced out of the gas reserves in the Netherlands. The production of green hydrogen will not be as flexible as the production of natural gas from the gas fields. The latter can cause availability problems or difficulties for the grid.
3. In the future when renewable electricity can be cheaply produced at specific locations due to the higher yields involved, it will be desirable to transport the energy. The energy supply in those specific production areas is higher than the demand. Electrolysis will be a solution to efficiently store and transport the energy surplus to areas of demand in the form of hydrogen. An efficient way to transport the hydrogen is in large ship tankers. When the national supply of hydrogen will become largely dependent on the imports of hydrogen, the system architecture of the Dutch natural gas grid needs to be suited to inject large volumes of hydrogen from imports. Political support is hence needed.

#### Responsibilities – Technical operational

1. The pipeline networks and the assets that are involved in the operation of the networks need a specific fixed gas standard to function. When a natural gas pipeline network is transformed to a hydrogen pipeline network it cannot be used for natural gas anymore and vice versa. The latter implies the notion that the gas standards of the specific parts of the current pipeline networks need to be determined ex ante its operation. The specific design of the network topologies of the transmission and distribution grids are hence essential looking at the gas that can be produced and consumed from specific qualities at the specific entry and exit points. The choices in specific gas qualities can create lock-in effects for the pipeline networks.

2. The underground storage facilities are currently sited in strategic places regarding the natural gas extraction, transport, and consumption. The underground hydrogen storage facilities are not dependent on the natural gas extraction anymore but on the production of hydrogen. The latter requires the storage facilities to be sited strategically regarding its interactions with other system components. The underground storage facilities are constrained by the geographical feasibility of the salt caverns.
3. The hydrogen production facilities are less dependent on a geographical location. Dependencies of the hydrogen production facilities are more on the characteristics as the availability of enough energy inputs and the possibility to inject hydrogen in the national grid. Blue hydrogen also requires the availability of CCS infrastructure and an underground CO<sub>2</sub> reservoir. The availability of a CO<sub>2</sub> reservoir is also geographically constrained. Green hydrogen is preferably produced nearby the electricity source due to the potential losses of the conversion and transport of the electricity.
4. Hydrogen production facilities can be dependent on storage facilities to take off their hydrogen surplus (i.e. especially the case with the decentralized production of hydrogen in for example micro-grids). For the more centralized production of hydrogen, the grid and large-scale hydrogen storage reservoirs can function as a buffer.
5. The CCS infrastructure is not present yet and needs to be constructed. The CO<sub>2</sub> storage facility needs to be located nearby the production facilities of blue hydrogen. The latter is a determinant of the siting of the blue hydrogen production facilities and the accompanying hydrogen storage reservoirs.
6. The decentralized production of hydrogen is currently unlikely to occur due to the costs of the decentralized storage. When the produced hydrogen is to be injected in the distribution grids, this would significantly challenge the topology of the grid.
7. The hydrogen production capacity adequacy on the short-term will be dependent on the production of blue hydrogen. Due to the centralized character and the large-scale investments this might create strong lock-in effects.
8. Steam methane reformation (SMR) of natural gas is the most desirable way of producing blue hydrogen. The natural gas dependency does hence not decline since enormous amounts of natural gas need to be converted to hydrogen. The natural gas extraction and the imports of natural gas need to continue. The current natural gas spot market is based on the trade of the volumes of natural gas in the Dutch transmission grid. When no natural gas is transported on such a large scale, bilateral trade will be the only viable option to transact the volumes of natural gas needed as the energy input for SMR.

### **Coordination – Technical operational**

1. Referring to point six of the previous section, the injection of decentralized produced hydrogen in the distribution grids requires technical coordination. The grid is currently designed on the top-down distribution of natural gas from the transmission grids to the consumers. It is a challenge to determine whether and on what scale and where the decentralized injection of hydrogen is possible.

### **Access – Economic-institutional**

1. The current laws and regulations applicable to the natural gas infrastructure, its operations, and the market functioning do not fit the utilization of hydrogen. It is an enormous challenge to formulate adequate laws and regulations for the utilization of hydrogen that are desirable.
2. The various production technologies of hydrogen include distinct characteristics in terms of supply patterns, up and downscaling times of the production, production capacities, operational and capital costs, and energy sources. The market for hydrogen needs to consider these distinctive characteristics and hence the different cost-structures of the production facilities. A challenge is to incentivize investments in capacity adequacy through a proper functioning market that simultaneously meet the economic and social goals of the system.

### **Responsibilities – Economic-institutional**

1. Producers need to enter the hydrogen production segment under certain conditions to safeguard the reliability of the system operations. Access regulation needs to be defined for both the centralized as the decentralized producers.
2. Since hydrogen requires large-scale investments in production, transportation, and end-use equipment, tariff-structures should be regulated to enhance the competitiveness of hydrogen compared to natural gas. The government should define a tariff structure that both address the large-scale investment uncertainty and the competitiveness to other alternatives.
3. Referring to point one in the previous sector, specific energy codes for a hydrogen infrastructure need to be defined. It needs to be clear which activities are publicly conducted and which privately.
4. Hydrogen properties differ significantly from natural gas. These properties require new industry standards to be formulated. Standards about the gas qualities, operational pressures, asset characteristics, and temperatures need to be standardized on a European level.

### **Coordination – Economic-institutional**

1. Supervisory bodies need to be in place to monitor and control access, the technical operations, and the market functioning.

## **9.6 Interview E. Huijzer – Grid strategist at Liander**

Date: 22/02/2019

### **Summary of interview**

#### **System architecture hydrogen infrastructure**

- The large-scale and centralized production of hydrogen will play a key role in a hydrogen infrastructure.
- Blue hydrogen will be produced on a large-scale from natural gas.
- Green hydrogen will be produced on a large-scale from offshore wind energy.
- The large-scale production of hydrogen is cost-effective and large customers can be supplied.
- Initiatives in the decentralized production of hydrogen, on the building level, are emerging. These initiatives are mainly all-electric systems that utilize hydrogen as a storage alternative. The development of hydrogen distribution grids from these initiatives will not emerge on the short-term.
- The end-use equipment in the built environment will be largely based on hydrogen condensing boilers. This is the logical option in terms of costs and psychological changes at the end-users.
- The most complex challenge of a transition to hydrogen gas is when decentralized hydrogen producers want to inject hydrogen in the distribution grid on a large-scale.

#### **Decentralized production of hydrogen gas**

- The potential developments of the decentralized production and injection of hydrogen in the distribution grids could be compared to the current developments of biogas. The distribution grid is not designed for the bidirectional flow of gas. The bidirectional flow of gas requires the gas to flow against the pressure in the distribution system. To increase the injection capacities of biogas connections, boosters are required.
- The decentralized injection increases both the operational system cost and the capital system costs.
- When hydrogen is produced decentral and need to be injected in the existing distribution grid, the developments of the bidirectional flow will occur. Another possibility is to construct new hydrogen infrastructure for the purpose of distributing the decentralized produced hydrogen. Different distribution grids will exist with separate functions.

#### **Centralized production of hydrogen gas**

- The logical route towards hydrogen as an energy carrier in the short-term will include mainly the centralized production of hydrogen. The decentralized production of hydrogen will become interesting when the production prices of centralized and decentralized production technologies converge.

### **End use equipment**

- Fuel cell heating systems are fundamentally different than condensing boilers.
- For new buildings a variety of heating systems is applicable.
- For the existing built environment, the most logical option is to replace the natural gas condensing boilers by boilers compatible with hydrogen. The transition to other heating systems would require more intensive adjustments to the buildings and habits of the owners and include larger investment costs.



### **Asset characteristics**

- The natural gas grid is suitable to transport hydrogen gas with the adjustments as described in the Kiwa and DNGVL report. There will be cases where assets need to be adjusted or replaced, but the main issue will be to replace the end-use equipment. Juridically there are still some issues of adjusting the natural gas grid to a hydrogen grid, but technically it is possible.
- The gas metering installations in the buildings need to be compatible with the higher gas flow rates of hydrogen. The pipelines in the houses need to be compatible with hydrogen gas and the condensing boilers need to burn hydrogen. The issue is if the end-use equipment is compatible with the higher gas flow rates and the different properties involved with hydrogen gas.

### **Network topology**

- The network topology of a hydrogen grid will become depended on the interaction with the electricity grids.
- The transport capacity of the electricity grid needs to be increased if the large-scale production of renewable energy is introduced. Nationally, it is expected that logical interactions of the gas infrastructure and the electricity infrastructure will be defined to accommodate the volatile nature of the renewable energy generation. Centrally, Groningen could be a logical location to realize such an interconnection. Decentral, there are also logical locations to realize the interconnections. The heat that is generated in the conversion of electricity to hydrogen can also be used efficiently when the conversion locations are sited strategically.
- The decentralized production of hydrogen will not occur on the same level as households produce solar energy. It is expected that the surplus of the households will be bought by an entity to produce hydrogen more efficiently.
- In the transition to hydrogen it will be organizationally hard to use the current natural gas infrastructure for the transportation of hydrogen. All the connections to a particular grid need to be converted to hydrogen connections when hydrogen is used as an energy carrier. In the beginning of the transition it will hence be possible that hydrogen pipeline infrastructure needs to be constructed that directly connects the producer with the consumers.
- It is possible that a variety of micro grids will occur. The distribution grids will hence only connect the micro grids and supply energy in times of scarcity. It could be possible that the distribution grids need to be scaled up if the supply from the transmission grid decreases.

### **Production capacity of hydrogen**

- The start of the transition will be dependent on the production of blue hydrogen. The first hydrogen supply will go to the industry. The transactions of hydrogen gas will be based on bilateral long-term contracts to secure the return on investments.
- In the built environment such long-term contracts are difficult due to the substantial number of consumers.
- Biomass gasification will also provide a small part of the hydrogen production capacity.

### **High calorific natural gas blending for the built environment**

- Currently the choice is politically made that high calorific gas will be imported and blended with nitrogen to be used in the built environment.

### **Market price determines the supply of hydrogen**

- Current studies towards the supply of hydrogen imply that hydrogen will first be used to satisfy the demand of the transport sector.
- Next to the transport sector, hydrogen will be used in the industry as a feedstock and for high-temperature heat.
- After the latter applications, hydrogen will be used to store the electricity surplus or supply the heat demand of the built environment.

### **Storage capacity of hydrogen**

- Next to decentralized storage capacity in large-scale underground storage facilities, the decentralized storage of hydrogen will also emerge. It could be more efficient to store hydrogen than inject it in the distribution grids.
- Storage will not be the bottleneck of the transition to hydrogen. There will be a variety of depleted gas reservoirs that are suited for the storage of hydrogen.
- The natural gas infrastructure currently includes a comprehensive storage infrastructure that can be converted to hydrogen storage capacity.

### **Political influence**

- The political influence will largely manifest itself in taxes and subsidies.
- The logical monopoly that the government has on the mining activities regarding natural gas will not be applicable anymore to the production of hydrogen.

### **Operational coordination of decentralized production and injection**

- Will be a challenging operation.
- The current energy codes are not adequate for the activities that are necessary to introduce hydrogen. Currently the advice towards the government is to let the system emerge in an experimental setting both privately and publicly.

### **Routines, emergency procedures, and preventive maintenance activities**

- Need to be changed to the nature of hydrogen but basically can continue in the way they are conducted now.
- Marking the specific pipelines will become more complex due the different gas standards that the network will distribute (i.e. biogas, natural gas, hydrogen, and admixtures of the latter). These gas standards can change during the transition to hydrogen.
- The coordination of these activities will become more complex, especially with third parties.

### **Degree of competition**

- When a wider variety of hydrogen producers emerge, more competition can be possible compared to the situation of the natural gas extraction.
- Distribution and transmission will stay publicly owned and operated.
- Storage will stay privately, as it is organized now.
- System operators could potentially provide the service of storage or conversion. With the conversion of electricity to hydrogen or vice versa, the involving conversion infrastructure could be publicly owned and operated. The trade of energy will stay a private activity, but the system operators will facilitate the transport and conversion.
- The retail market can still exist for the end-users.

### **Fairness of transition to alternative of natural gas**

- With the regional energy strategies, the end-users cannot choose which alternative they will get. The price of the alternatives of the grid connections are hence also determined by the regional energy strategies.
- The end-users need to be protected against high prices regarding the chosen regional energy strategies.

### **Energy content transported through the gas grid when hydrogen replaces natural gas**

- The energy content of the hydrogen that needs to be transported through the gas grid will decrease due to insulation measures and the other alternatives that will replace natural gas (i.e. such as all electric and district heating).
- Currently studies report variations in the potential supply of hydrogen. It is argued that approximately 15 to 60 percent of the current natural gas demand will be replaced by hydrogen.

- This does not imply that the distribution grids include enough transport capacity. The neighborhoods that adopt district heating or all-electric will not need a gas grid connection anymore. On the higher-pressure levels, it is expected that the gas grids will not be decommissioned.

### **Tariffs**

- The bilateral market price will be dependent on the price agreements of the large-scale producers and customers.
- When hydrogen is distributed to the built environment, tariffs need to be regulated for the protection of the end-user. The government can do this through the variety of energy taxes.
- The government can play a key role in tariffs with the variety of subsidy and tax instruments.
- Interesting is to determine if both the consumers and producers need to pay for the development of a hydrogen grid. Currently only the consumers are paying the grid. With a more decentralized nature of the production, it can be desired to change this.
- Tariffs will increase due to the large investment costs.

### **Distribution level balancing**

- Due to the emergence of the decentralized production of gas it is expected that the distribution operators will become partly responsible for the balancing regime of the natural gas grid. This would largely mean that the distribution operators are balancing the grid on a day-to-day basis. Seasonal fluctuations will still be the responsibility of the TSO.

### **Organization of transactions in distribution grid**

- Technically the distribution system operators are ensuring that the producers can inject their gas. If the demand is available is another question and not the responsibility of the DSO.
- Currently biogas producers are responsible for the metering and the quality of the gas that is injected.

### **Industry standards and normalization**

- Countries can formulate their own national standards on safety. In practice these standards are formulated on a European level due to the scale of the sector.
- In Europe a lot of developments are underway regarding the normalization of hydrogen standards. A normalization platform in the Netherlands exist to come to European wide industry standards.
- The first pilots can be conducted without industry norms and standards. When hydrogen is integrated on a large-scale, these norms and standards need to be available.
- European normalization is hence going ahead of the market to accommodate the latter.

### **Bottlenecks in energy codes**

- Roles and responsibilities are unclear. The playing field is yet undefined.
- Hydrogen producers need to emerge.
- The hydrogen needs to be transported, traded, and stored.
- Entities potentially need to manage the conversion capacity.
- Who is responsible for the technical and economic risks that need to be taken?

### **Role of government in determining the playing field**

- Currently the government is not defining the playing field yet.
- This is a prudent solution since a well-defined playing field can generate certain undesirable lock-in effects due to the uncertainty that exists. Currently no hydrogen infrastructure exists to define a playing field for.

### **Vertical and horizontal integration**

- Horizontal integration of heat, natural gas, hydrogen and electricity is important regarding the laws and regulations that exist now.
- All the separate acts for gas, heat, electricity, and potentially hydrogen and CO<sub>2</sub> do not enhance the investments in renewable energy production capacity. With the intertwined nature of a hydrogen and an electricity infrastructure it is desirable that investments in renewable energy capacity can be financed from the various sectors regardless of which energy carrier is used. With the separate laws this is currently impossible.
- From this viewpoint the business case for hydrogen could be positive on an energy system level of a country but not on the specific energy infrastructure level.
- The latter requires the laws and regulations to be adapted to address the nature of the total system efficiency in terms of costs.
- Vertical integration could be desirable on the small-scale. Currently the vertical integration of distribution and transmission activities with commercial activities is prohibited. In the transition period, vertical integration could possibly help. But the overall thoughts are that the current unbundling of activities is desirable.

### **Pitfalls of transition**

- Most of the discussions about the alternatives to natural gas are about small parts of the total system. Important is that a transition to hydrogen needs to be viewed from a system perspective on the total system costs.
- Moreover, discussions are often about the starting point of the transition and the result of the transition. The transition itself is the most important.
- Sustainability is determined by the energy source and the costs are determined by the energy carrier.

### **System perspective**

- It is important that the system perspective of alternatives to natural gas become transparent and clear. Currently a large part of the discussion is conducted on the level of the end-use equipment and the involving energy carriers. The latter does not solve the CO<sub>2</sub> problem since the CO<sub>2</sub> emissions are dependent on the energy source.

### **Changing gas Act and energy codes**

- An important first step can be to allow the public utilities to start hydrogen projects (i.e. to make the gas act and energy codes applicable to hydrogen).
- A lot of laws and regulations currently applicable to natural gas can be used with hydrogen.

## **Changes positioned within Comprehensive Design Framework**

### **Changes in the technical-operational dimension**

#### **Access**

#### **System architecture**

- More producers will need to interact with the distribution system when the share of decentralized hydrogen production grows.

### **Asset characteristics**

- The production segment of hydrogen will be depended on various energy sources as natural gas and renewable energy. The production of blue hydrogen from natural gas will be dependent on CCS.
- The natural gas condensing boilers in the built environment will be largely replaced by hydrogen condensing boilers.
- The application of fuel cell heating systems is fundamentally different than the application of condensing boilers.
- The end use-equipment including the pipelines, metering installations, and the condensing boilers need to be compatible with higher gas flow rates and the combustion of hydrogen instead of natural gas.

### **Responsibilities**

#### **Network topology**

- The large-scale decentralized production and injection of gas needs the gas to flow bidirectional instead of unidirectional. Boosters are required.
- Micro-grids can emerge when hydrogen is produced locally.
- The production of green hydrogen is basically a conversion process of electricity to hydrogen. This process will cause the gas grids to converge with the electricity grids. The locations where the electricity and gas grids need to interact need to be chosen strategically.
- The decentralized production of hydrogen will not occur on the household level, but it is expected that the electricity surplus will be bought by a third party to produce hydrogen.
- In the transition to a hydrogen infrastructure, direct pipeline connections between producers and consumers are likely to occur.

#### **Production, grid, and storage capacity**

- The production of hydrogen will be largely based on steam methane reformation. It is likely that the first supply of hydrogen will be consumed by the transport sector and the industry.
- When enough renewable energy capacity is installed hydrogen will be produced green.
- Biomass gasification will also provide a small part of the green hydrogen production capacity.
- Hydrogen can be stored in the same central way as natural gas. The natural gas storage facilities need to be converted to hydrogen.
- The decentralized storage of hydrogen can occur if it is more efficient to store it locally than to inject in the public grids.
- The total energy content that will be transported through the grid will decline due to the insulation measures and the alternative heating options such as all-electric and district heating. This does not imply that the distribution grids include enough distribution capacity.

#### **Redundancy planning**

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#### **Ownership and decision rights**

- Storage and conversion infrastructure could be publicly owned and operated.

#### **Coordination**

##### **Operational coordination**

- The decentralized production of gas requires a more complex and costly operation of the distribution grids.
- When large shares of decentralized produced hydrogen gas are injected in the distribution grids, the day-to-day balancing role of the DSO will get more intensive.

## **Routines, emergency procedures, and preventive maintenance**

- The safety instructions need to be changed to be applicable to hydrogen.
- The marking of the pipelines will become more complex since different gas standards can flow to the networks (i.e. green gas, natural gas, hydrogen gas, and admixtures). The third-party coordination and communication of the marking activities will become more complex.

## **Changes in the economic-institutional dimension**

### **Access**

#### **Competition and state intervention**

- The production segment of hydrogen will become more open since the logical monopoly of the government on the natural gas extraction will not exist anymore. More producers can be allowed which can result in more competition.
- System operators could potentially provide conversion or storage services. The trade of gas will stay a private activity, but the system operators will facilitate the transport and conversion services.
- End-users in the built environment will, because of the regional energy strategies, not have the option to choose the energy carrier that they want to consume.
- The government should be careful in defining the playing field since no hydrogen infrastructure exists yet. Lock-in effects could be created due to the uncertainty and bounded rationality of the government.

### **Responsibilities**

#### **Laws and regulations**

- The current energy codes and the Gas Act are not applicable to hydrogen and need to be changed.
- System operators are currently not allowed to participate in any hydrogen related activities apart from experimental projects. The same applies to the storage operators. This needs to be changed.

### **Access regulation**

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### **Tariff regulation**

- Laws and regulations need to protect the end-users from unfair prices, especially when they have no choice due to the regional energy strategies.
- The government can play a key role in the regulation of the hydrogen tariffs. The costs of the investments in the new hydrogen infrastructure need to be covered by the tariffs.

### **Ownership and decision rights**

- The roles and responsibilities need to be defined and stated in the laws and regulations.
- It needs to be determined which entities become responsible for the various economic and technical risks of the activities involved in the provision of hydrogen.
- New ownership and decision rights need to be formulated for the hydrogen production/conversion segment.

### **Spot market rules**

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### **Industry standards**

- Hydrogen standards need to be formulated and stated in the laws and regulations when hydrogen is integrated.

## Coordination

### Contractual arrangements and modes of organization

- The transactions of the volumes of hydrogen will be based on long-term contracts to secure the return on investments.
- In the built environment such long-term contracts will need to be established between the energy suppliers and the producers. (challenge is to secure that the small-scale consumers are also subject to these long-term arrangements).

### Horizontal and vertical integration

- The horizontal integration of heat, natural gas, hydrogen, and electricity is desirable since it would encourage the efficient operation of the total energy system.
- Vertical integration could be desirable on the small-scale production and distribution of hydrogen. The laws and regulations should be adjusted to allow the system operators to participate in commercial activities.

### Principal-agent and opportunistic behavior safeguards

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What challenges are there?

	Technical-operational	Economic-institutional
<b>Access</b>	<ol style="list-style-type: none"> <li>4. Integrating more producers with various characteristics.</li> <li>5. To determine which technologies should make up the hydrogen production segment.</li> <li>6. The hydrogen infrastructure needs to interact with CCS infrastructure.</li> <li>7. To determine which technologies should make up the storage segment.</li> </ol>	<ol style="list-style-type: none"> <li>7. To determine whether the production of hydrogen is a private or public activity.</li> <li>8. To determine whether the end-user has the right to choose an energy carrier.</li> <li>9. Formal institutions for hydrogen need to be formulated.</li> <li>10. To determine whether the various energy acts need to be merged.</li> <li>11. To determine whether system operators need to be unbundled.</li> </ol>
<b>Responsibilities</b>	<ol style="list-style-type: none"> <li>6. Determine new entry points in the public grids.</li> <li>7. Determine interconnection points between the electricity and natural gas grid.</li> <li>8. The production capacity needs to emerge.</li> <li>9. To allow for the bidirectional flow of gas in the distribution grids.</li> <li>10. Conversion of natural gas underground storage facilities to hydrogen storage facilities.</li> <li>11. Ownership and decision rights regarding the gas quality and</li> </ol>	<ol style="list-style-type: none"> <li>10. To determine how hydrogen producers can enter the market at which level.</li> <li>11. The laws and regulations need to address the decentralized injection of hydrogen.</li> <li>12. Industry standards need to be formulated regarding the hydrogen production, storage, transportation, and end-use technologies and activities.</li> <li>13. To determine how the hydrogen production activities are interwoven with the CCS activities.</li> </ol>

	<p>the safe operations need to be defined.</p> <p>12. The decentralized injection of hydrogen gas requires a more intensive day-to-day balancing role of the DSO.</p>	<p>14. To determine how the decentralized produced hydrogen will be transacted.</p> <p>15. To allow the storage and transportation actors to participate in the provision of hydrogen.</p> <p>16. To determine whether DSOs can merge the various distribution activities (i.e. heat, electricity, and gas).</p> <p>17. The mining act needs to be adjusted to allow for the underground storage of H<sub>2</sub></p>
<b>Coordination</b>	<p>3. The decentralized injection of hydrogen gas requires a more complex and costly distribution grid to emerge.</p> <p>4. Safety instructions need to be formulated regarding the hydrogen activities.</p> <p>5. The marking of pipelines becomes a larger challenge.</p>	<p>4. Modes of organization to accommodate large-scale investment risk are necessary.</p> <p>5. To secure the investments in the built environment.</p>

### Explanation of the challenges

#### Access – Technical operational

1. The production of hydrogen is a conversion process. Various energy sources can be converted to hydrogen. Due to this nature several hydrogen production technologies are possible including distinctive characteristics in terms of capacity, costs, environmental impact, and source dependency. The production of hydrogen can also be conducted locally on a more decentralized level. The nature of the hydrogen production hence differs from the production of natural gas and includes other interactions at various locations with the public gas grids. The challenge is to integrate the various technologies successfully. That is, to ensure the system performance.
2. Since different hydrogen technologies are possible it needs to be determined which technologies will be viable to make up the production assets of the system. Determinants such as costs, environmental impact, capacities, energetic performance, et cetera, determine the viability of the hydrogen production technologies. The challenge is that it needs to be determined which production technologies can emerge.
3. When blue hydrogen is produced, CCS is needed to capture and store the CO<sub>2</sub>. This implies that the hydrogen production infrastructure needs to be interwoven with CCS infrastructure. The challenge is to formulate how this interaction can occur.
4. Hydrogen storage technologies are like the storage technologies that are possible for natural gas. The challenge is to formulate which storage technologies can be exploited.

#### Responsibilities – Technical operational

1. The introduction of other production technologies does also imply that the production of hydrogen can take place on various locations. The challenge is not to determine which locations are appropriate but to determine the locations of new entry points in the public grids.
2. When hydrogen will be converted from the renewable electricity surplus, these facilities need to be sited. The production/ conversion facilities will function as the interconnection between the electricity and gas grid. Hydrogen can also be produced directly without the interference of



the electricity grids. The challenge is to determine where these conversion facilities will be sited and if they will function as an interconnection point between the electricity and gas grids. Different variations are possible.

3. The production capacity of hydrogen is currently insufficient to replace the needed demand for heating in the built environment. The challenge is to enhance the development of hydrogen production capacity.
4. When hydrogen is injected on the level of the distribution grids and it needs to be transported to the transmission grid the grids needs to be adjusted to a bidirectional flow of gas. The challenge is to determine the bidirectional capacity that is needed.
5. Natural gas storage underground storage facilities need to be converted to hydrogen storage facilities to store hydrogen underground. The challenge is to determine how gas will be stored in the future and which storage capacities are enough.
6. Gas quality standards need to be established and safety standards need to be formulated regarding the activities of the hydrogen provision. These standards need to be controlled and enforced. The challenge is to define ownership and decision rights that determine which entities are responsible for the monitoring and control of the gas quality and safety standards.
7. The decentralized injection of hydrogen requires the system operators to intensify their day-to-day balancing role. The challenge is to determine how this role can be covered.

#### **Coordination – Technical operational**

1. The decentralized injection of gas on the distribution level is bounded to certain injection capacities that vary for the different grids. Higher pressure grids can adopt large volumes of gas. The challenge is to determine the operational coordination of a bidirectional gas flow per decentralized producer.
2. The regulations regarding the operational coordination of the various natural gas activities are defined and stated in the energy codes and regulations such as the BEI and the VIAG. The challenge is to construct similar codes and safety instructions.
3. Pipeline marking becomes more complex when various gas standards are applicable.

#### **Access – Economic-institutional**

1. The conversion/ production process of hydrogen can be conducted in many ways on various scales. The challenge is to determine which specific activities can be privately or publicly owned and operated.
2. With the regional energy strategies, municipalities will determine which alternatives to natural gas are convenient where. This would imply that an individual consumer would not have a choice in energy carrier. The challenge is to determine how the process of allocating alternatives to natural gas will be performed and if end-users will have a choice.
3. Currently no formal institutions regarding a hydrogen infrastructure are in place yet. The formal institutions of the natural gas infrastructure are extensive. The challenge is to determine which laws and regulations will be appropriate for hydrogen and which laws and regulations will not cause negative lock-in effects.
4. Currently the gas infrastructure, the district heating infrastructure, and the electricity infrastructure have separate Acts applicable to the provision of energy. The challenge is to determine for the energy provision to the built environment whether it is desirable to merge these acts.
5. Currently system operators are not allowed to participate in any commercial activities. The challenge is to determine if this must still be applicable. Are system operators for example allowed to in participate in small scale hydrogen production, storage, and conversion activities?

### **Responsibilities – Economic-institutional**

1. Currently natural gas producers can enter the market via the extraction permits. Its needs to be determined how hydrogen producers can enter the market for production. The challenge is to formulate access regulation that addresses the different hydrogen production activities on varying scales.
2. Currently with the injection of natural gas the system operator has a connection obligation but not a transport obligation. The challenge is to determine whether this system is adequate with hydrogen or not.
3. Industry standards need to be formulated for the hydrogen production, storage, transportation, and end-use technologies and activities. Standards regarding the technologies and the installations activities need to be established before hydrogen can be utilized.
4. The production of blue hydrogen will need CCS to capture and storage the CO<sub>2</sub>. It needs to be determined which parties can participate in CCS activities and what the delineation is of hydrogen production and CCS activities. The challenge is to formulate this within the laws and regulations.
5. The decentralized production of hydrogen gas can be transacted on the wholesale market. It needs to be determined whether a market needs to emerge on a lower level.
6. Currently the Dutch laws and regulations prohibit the public entities and underground storage operators to participate in hydrogen related activities. This should be adjusted.
7. Distribution system operators currently need to unbundle their electricity and gas activities. The challenge is to determine whether these activities should be unbundled or not.
8. Currently the Dutch Mining Acts does not allow the underground storage of hydrogen. The challenge is to adjust the laws and regulations to allow for the underground storage of hydrogen.

### **Coordination – Economic-institutional**

1. Large scale investments are needed to realize the production, transportation, storage, and end-use technologies. The challenge is to formulate a proper mode of organization to accommodate the investment risks.
2. The built environment includes many individual consumers that are accommodated under various energy suppliers. Long-term arrangements with the energy suppliers become more complex since a mode of organization needs to exist that ensures the demand for hydrogen over a longer period. The challenge is to formulate a mode of organization that ensures the demand for hydrogen over a longer period.

## **9.7 Interview Pascal te Morsche – Senior policy advisor gas at Liander asset management**

Date: 22/02/2019

### **Summary of interview**

#### **Decentralized production and storage of gas**

- Agreements about the supply in the distribution grids between the producers and distribution system operators (DSOs) are necessary.
- Important is to determine where the local storage of hydrogen occurs. Buffer capacity is necessary when gas is injected the distribution grids. Currently buffer capacity of biogas is realized at the producers. When the decentralized production of hydrogen increases, larger storage facilities will be necessary. The question is where these large-scale storage facilities will be sited and who will operate them.
- Large storage facilities will be operated by third party private companies. The smaller-scale storage facilities can be owned by the producers or DSOs.

- Hydrogen injection in the distribution grids will probably not occur on the level of households but rather on the level of neighborhoods.

### **Storage of hydrogen**

- The decentralized storage of hydrogen will be dependent on the costs of the storage facilities. When the centralized storage of hydrogen is more cost-effective for a small-scale producer it will be likely that these storage services are contracted.
- In the natural gas infrastructure, storage is merely a centralized activity. When hydrogen is produced locally, storage could also be feasible on a decentralized level. Smaller volumes of hydrogen could hence be stored locally.
- Larger volumes of hydrogen will still be stored on a central level.

### **Hydrogen micro grids**

- Hydrogen micro-grids that emerge, because of the decentralized hydrogen production on the level of households, will probably be managed and operated by the distribution operators.
- The latter could facilitate the market functioning of these grids. Moreover, it is cost-efficient to use the existing distribution grids to connect the households with the higher-pressure grids.
- Another advantage is that if the micro grids are publicly owned, they are accessible for third parties.

### **Asset characteristics and asset management**

- The recommendations of the Kiwa report are currently further investigated.
- The materials used in the grid will not cause significant problems. Seals and metering installations are currently tested.
- The instructions and apparatus that are needed for the management and maintenance of the assets need to be slightly adjusted when hydrogen is integrated.
- For natural gas a “VIAG” exist that states the safety instructions for the management of the natural gas infrastructure. These safety instructions also exist for biogas and are currently also developed for hydrogen. Per eventuality the natural gas safety instructions are adjusted to the requirements of hydrogen.
- The end-use equipment at the end-user need to be replaced.

### **Experimental projects**

- The system operators are focusing on the technical operational issues of the hydrogen infrastructure. With knowledge about these issues, the first experimental projects are realized to demonstrate the possibilities of a hydrogen infrastructure and to show that the operation is safe and efficient.
- The government should adjust the laws and regulations applicable to the gas infrastructure to make such projects possible.
- Experimental projects need to be funded by subsidies to pay off. Large-scale investments will otherwise not occur.

### **Bottlenecks in laws and regulations**

- Distribution system operators are not allowed to participate in hydrogen activities. It is important to demonstrate that hydrogen functions safely and adequate.

### **Industry standards**

- Gas quality standards need to be formulated. Different end-use applications require different gas qualities and cleaning steps can be included. These gas standards need to be formulated and stated in the laws and regulations.

### **Injection capacity of the distribution grid**

- When a decentralized hydrogen producer wants to inject hydrogen in the distribution grid it will be dependent on the possibilities of the existing distribution and transmission grids. The siting process will be dependent on the availability of electricity surplus.
- If the current distribution grid topology is used, it needs to be determined what the injection capacity is of the location where the production facility is sited.
- Higher pressure networks include higher injection capacities. Investment can be needed to connect a producer with higher pressure networks. Currently, agreements are nationally formulated to determine how much money a system operator can invest in the extra infrastructure that is needed for the biogas connections.
- With biogas it is currently hard to predict what the locations going to be of the decentral production facilities. The regional energy strategies can be used to guide the siting process of the hydrogen production facilities. The network can be adapted to the injection of the latter volumes.
- Hydrogen production facilities will be less dependent on a specific location compared to biogas production facilities. The latter implies advantages for the manageability of the decentralized hydrogen injection.

### **Network topology**

- When it becomes clear where the production and storage facilities will be sited it becomes more easier to determine whether booster capacity needs to be installed and the capacity of the grid needs to be increased or whether new pipelines need to be constructed to connect producer with higher-pressure grids.
- With the integration of more decentralized hydrogen production facilities, smaller hydrogen grids can occur that are still linked to the distribution grid. Less supply will be needed from the transmission grids since the production of hydrogen occurs locally. Shortages in the local production of hydrogen will be compensated by the buffer capacity of the transmission grid and the including storage facilities. In summer times (i.e. low demand for gas in distribution grid), the decentralized production facilities can supply the transmission grid and storage facilities connected to the transmission grid.
- The system design of the grid is based on the unilateral flow of gas by the reduction of the grid pressures from the top to the bottom (i.e. from the start of the transmission grids to the end of the distribution grids). With the development of the decentralized production of biogas, gas needs to flow from the lower pressure grid to the higher-pressure grids. With the large-scale integration of decentralized production facilities of hydrogen these dynamics are applicable too.

### **Bidirectional flow versus pipeline construction**

- The choice to transport gas towards higher-pressure networks through the public distribution grids or through a bypass is dependent on the capacity that is to be injected and the costs of the options to boost the injected gas or construct new pipelines.
- Currently the bidirectional flow of natural gas in the distribution grids is not possible since the technologies are not yet installed. The stations need to be expanded with extra compression units to allow for the bidirectional flow of gas. Currently boosters are tested for a gas flow from the 100-mbar grids to the 8-bar grids and from the 8-bar grid to the 40-bar grids. The technology is not the problem, these technologies already exist.

### **Production capacity**

- The production of blue hydrogen will be necessary to start the transition to hydrogen and reduce the CO<sub>2</sub> emissions on the short-term. The integration of blue hydrogen production capacity on the short-term is necessary since the largest organizational challenge of the transition will exist in the installation of the end-use applications at the consumer.

- The Dutch government will not be involved in the production of hydrogen. Contracts will exist regarding supply obligations in which the supply can be arranged publicly.

### **Redundancy planning**

- There is no need to make the redundancy planning of the grid more intensive with hydrogen. The developments in insulation measures will decrease the need for redundancy measures since outages will cause less severe effects. Hybrid heating systems at the end-users can potentially switch from energy carrier.

### **Gas standards**

- Gas standards need to be established per grid. For the local production of gas, it could be possible that the separate grids include separate gas standards.

### **Competition**

- More competition will exist on the production level.
- The storage segment will become more competitive compared to the current situation with natural gas. The hydrogen reserves need to be managed differently than the natural gas reserves.
- More competition regarding balancing capacity can be allowed in the distribution grids.
- Micro-grids can emerge but the connection between various grids need to be publicly owned.

### **Access regulation**

- The hydrogen production segment should be open to anyone who wants to and is able to produce. Everyone who wants to produce hydrogen can inject hydrogen in the public grids if it matches the gas quality standards. The system operators are still responsible for the quality of the gas within their grids.
- Distribution and transmission activities stay publicly owned.

### **Ownership and decision rights**

- The ownership and decision rights of the various entities stay like those in the natural gas infrastructure.
- The security of supply needs to be addressed differently due to the different nature of the production of hydrogen compared to natural gas.

### **Tariff structure**

- Natural gas and hydrogen prices will eventually converge due to the CO<sub>2</sub> costs included in natural gas and the developments regarding the hydrogen technologies.
- The transportation costs of hydrogen will increase due to the investments needed in the hydrogen technologies. A large share of the investments can be mitigated if they are combined with the already planned replacements of assets and the already planned construction activities. The transportation costs will hence not increase significantly

### **Industry standards**

- The predominant share of the existing industry standards can be adopted and are still applicable when hydrogen is used as an energy carrier. The remainder share of the industry standards need to be slightly adjusted to be compatible with hydrogen.

### **Energy codes**

- The most important bottleneck is that the system operators cannot be involved in hydrogen related activities, apart from experimental projects. This hampers the development of hydrogen grids.

- Standard gas qualities need to be formulated.
- With new gas standards and the allowance to participate in hydrogen related activities, the current energy codes will be largely applicable to hydrogen.

### **Transition from natural gas grid to hydrogen grid**

- From a system perspective it is inefficient to give end-users a choice in the energy carrier that is distributed to their buildings. It will be cost-effective to allocate certain areas to a specific energy carrier.
- The allocation of the energy carriers to specific areas and end-use applications should be a regulated activity to enhance the system efficiencies.

### **Balancing regimes system operators**

- The decentralized production of hydrogen will not be problematic since the injection capacities are regulated in bilateral contracts between the system operators and the producers. These contracts need to fulfill certain requirements stated in the energy codes.
- System operators have the obligation to connect producers to the grid but do not have the obligation to transport certain volumes of gas. This mechanism will probably stay in place.

### **Production and storage capacity adequacy**

- The market should determine whether the investments in production and storage capacity will be viable. The government can incentivize these investment decisions in several ways.
- To safeguard the security of supply, contracts need to exist to ensure certain volumes of supply and to ensure the flexibility in the up and downscaling of the supply. These contracts should be long-term contracts.

### **Horizontal and vertical integration**

- From a system cost perspective it will be efficient to integrate the various transport activities of the separate grids (i.e. heat, electricity, and gas) in an area within one public entity. The latter will be dependent on the scale of the grid and the number of end-users.
- Vertical integration can be desirable in the production and storage activities. The other activities hence remain unbundled.

## **Changes positioned within Comprehensive Design Framework**

### **Changes in the technical-operational dimension**

#### **Access**

#### **System architecture**

- With the decentralized injection of gas in the distribution grids it is important to determine where the buffer capacity is sited. When buffer capacity is sited at the decentralized producers, new storage facilities need to emerge. When hydrogen is stored centrally, the decentralized produced hydrogen needs to be transported to the higher-pressure grids.
- Hydrogen micro grids can occur that need to interact with the public grids.
- The decentralized injection of large shares of gas will change the top-down nature of the system architecture. Gas will also flow from the distribution grids to the transmission grids. The latter will reduce the supply from the transmission grids to the distribution grids and increase the supply from the distribution grids to the transmission grids.

#### **Asset characteristics**

- The natural gas condensing boilers at the end-users need to be replaced by either a hydrogen condensing boiler or a fuel cell heating system. The metering devices need to be adjusted to the higher gas flow rates necessary to transport the same energy content as with natural gas.
- For the decentralized injection of large volumes of hydrogen boosters are required to achieve a bidirectional gas flow.

## **Responsibilities**

### **Network topology**

- New hydrogen pipelines can be constructed on a decentralized level that transport the locally produced hydrogen to a pivotal point where it is stored or from where it is injected in the public distribution grid.
- The location of the green hydrogen production facilities will largely be based on the availability of renewable electricity surplus and the possibilities to store the hydrogen or inject it in the public grids.
- The injection of large volumes of gas in the low-pressure grids is costly, it needs to be determined whether the distribution grids needs to be adjusted to the bilateral flow of gas or whether a decentralized producer needs to be connected to the higher-pressure grid. The latter decision is a decision in terms of cost and operational manageability. The distribution grids need to be developed to adopt the larger volumes of decentralized injected hydrogen.
- Hydrogen production facilities will be less dependent on a specific location compared to the biogas production facilities.
- The siting of the production and storage facilities on a decentral level will determine how the grid needs to be adapted.

### **Production, grid, and storage capacity**

- The production capacity of green hydrogen will be dependent on the availability of renewable electricity surplus.
- The transportation capacity of the distribution grid can be a constraining factor if decentralized hydrogen producers want to inject gas into the grid.
- When the share of the local hydrogen production increases, the transmission grid will supply the buffer capacity that is needed in winter times.
- Blue hydrogen capacity will be necessary to facilitate the transition to a hydrogen infrastructure.

### **Redundancy planning**

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### **Ownership and decision rights**

- System operators need to be allowed to own and operate hydrogen assets.

### **Coordination**

#### **Operational coordination**

- The integration of a large share of decentralized produced and injected hydrogen requires the distribution grids to be coordinated differently. The day-to-day balancing becomes more intensive and gas will flow bidirectional instead of unidirectional.

### **Routines, emergency procedures, and preventive maintenance**

- The safety instructions and apparatus that are needed for the management and maintenance of the assets need to be adjusted to the changing requirements of hydrogen.
- Safety instructions need to be formulated just as with natural gas and biogas.

### **Changes in the economic-institutional dimension**

#### **Access**

#### **Competition and government intervention**

- More competition can be allowed in the production segment.
- The storage segment will become more competitive due to the nature of the hydrogen production and storage.

- More competition for balancing capacity can be allowed in the distribution grids.
- Micro grids can emerge on a decentral level. These grids can be owned and operated privately or publicly.
- The hydrogen production will be privately owned and operated. The government will need to intervene to ensure the security of supply.
- The consumer sovereignty could decrease by the implementation of the energy strategies and the preference towards system efficient solutions.
- An energy system efficiency viewpoint would imply that it would be useful to merge the various distribution activities of electricity, heat, and gas. This would fundamentally change the way in which the end-users pay for energy and the way in which the system is organized.

## **Responsibilities**

### **Access regulation**

- The Gas Act and energy codes should be adjusted to allow the system operators to participate in activities related to the provision of hydrogen.
- The hydrogen production segment should be open to anyone who wants to and is able to produce hydrogen. The injection of the produced hydrogen needs to match the strict gas quality standards.

### **Tariff regulation**

- The costs of energy will increase on the short-term due to the large-scale investments that are needed.
- When the distribution activities of the various energy carriers merge, the tariff structure would fundamentally change since energy can be traded differently and the costs of transportation can be socialized differently.

### **Ownership and decision rights**

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### **Spot market rules**

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### **Industry standards**

- Industry standards need to be formulated and the current standards need to be assessed in terms of their applicability to the provision of hydrogen.
- Hydrogen gas standards for the transportation grids and the accompanying end-use applications need to be formulated and stated within the laws and regulations.

## **Coordination**

### **Contractual arrangements and modes of organization**

- The security of supply will no longer be dependent on the dominant involvement of the government as with the mining activities. Production capacity adequacy mechanisms need to exist in the form of long-term contracts.
- The market should, with proper investment incentives, determine which investments are viable to make.

### **Horizontal and vertical integration**

- The storage and production of hydrogen could be combined activities owned and operated by the same entity.



- The distribution activities in an area regarding the various energy carriers could be accommodated under a single entity. There will no longer be a distinction between the various energy carriers, but the service will become the delivery of energy services.

**Principal-agent and opportunistic behavior safeguards**

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What challenges are there?

	<b>Technical-operational</b>	<b>Economic-institutional</b>
<b>Access</b>	8. To determine the degree of decentralized and centralized production and storage. 9. Large scale local injection will change the top-down system architecture. 10. Changing end-use equipment.	12. To determine whether storage activities are publicly or privately owned. 13. To determine whether competition can be allowed in the production of hydrogen and where. 14. Consumer sovereignty. 15. Formulation of formal institutions energy delivery to built environment.
<b>Responsibilities</b>	13. Define ownership and decision rights regarding various storage and production assets. 14. Local entry points. 15. Occurrence of local micro-grids.	18. Path dependency of the emergency of the demand and the emergence of production, storage, and transportation capacity. 19. The Mining Act, Gas Act and energy codes do not address the hydrogen activities. 20. To determine ownership and decision rights of hydrogen micro-grids. 21. Injection regime hydrogen. 22. Access regulation for hydrogen producers and storage operators. 23. Tariff structure of hydrogen for end-users. 24. Industry standards.
<b>Coordination</b>	6. Coordination of decentralized injection. 7. Safety instructions and apparatus.	6. Formulation of modes of organization to secure supply. 7. Control and enforcement. 8. Day-to-day balancing of DSO

**Explanation of the challenges**

**Access – Technical operational**

1. A fundamental choice in the system architecture will be where the buffer capacity of the built environment will be located. This is dependent of the degree of centralized and decentralized production. When the production is organized centrally, storage will also be organized centrally. The buffer capacity is hence organized centrally and connected with the transmission grid. When a large share of hydrogen is produced locally, buffer capacity can

also exist on the local level. The challenge is to determine whether the production and storage of hydrogen should be conducted locally or centrally.

2. The large-scale injection of hydrogen on a local level will change the system architecture from a top-down oriented system towards a system that facilitates the flow from the transmission networks to the distribution networks and vice versa. The challenge is to determine to which degree the local injection and storage of hydrogen is desirable and should be allowed.
3. Natural gas condensing boilers can either be changed for hydrogen condensing boilers or for fuel cell heating systems. The choice in such systems and the restrictions on the choice determines to a large extent how the system will be designed. The challenge is to determine whether the end-use application can be freely chosen or not.

#### **Responsibilities – Technical operational**

1. Ownership and decision rights regarding the production and storage assets need to be formulated. These ownership and decision rights will determine which entities will be allowed under what conditions in the service provision of hydrogen. The challenge is to determine these rights for the several types of production activities on the various levels in the system.
2. Entry points in the distribution grids need to be constructed when hydrogen is produced locally. The challenge is to determine where these entry points are possible per specific producer.
3. With a highly decentralized nature of the hydrogen production, local micro-grids can occur. The systems need to be owned and operated. The challenge is to determine how the operation and design of these systems will be regulated.

#### **Coordination – Technical operational**

1. The local injection of hydrogen in the distribution grids need to be arranged by the distribution system operators. When producers want large volumes to be injected, the grid needs to be adjusted or the producers need to be connected to higher-pressure grids. When the gas is injected and the demand for the locally produced hydrogen is too low, the bidirectional flow of hydrogen gas to the transmission grid needs to be possible. The latter requires investments in the grid. The challenge is to determine which operational coordination model is adequate to accommodate the locally produced hydrogen.
2. Safety instructions need to be formulated for hydrogen. The apparatus involved in the asset management activities need to be adjusted to be compatible with hydrogen. The challenge is to determine which safety instructions are still applicable and to determine where new safety instructions should be formulated.

#### **Access – Economic-institutional**

1. Storage activities vary in scale and nature. It needs to be determined what entities, public or private, can participate in which storage activities on what scale. The challenge is to define the storage activities that are desirable and to allocate the ownership and decision rights of these activities.

#### **Responsibilities – Economic-institutional**

1. For a hydrogen transportation and storage infrastructure to emerge, enough supply and demand must exist. The challenge is to facilitate the emergence of the supply and demand for hydrogen.
2. The Mining Act, The Gas Act, and the energy codes need to be adjusted to be compatible with hydrogen. Currently it is not possible to store hydrogen underground and to transport hydrogen through the public gas grids. The challenge is to change the current laws and regulations and to formulate laws and regulation that address the desirable path for hydrogen. The latter is the most difficult challenge since lock-in effect can be created with certain laws and regulations.
3. When hydrogen micro-grids emerge, it is important that ownership and decision rights are defined within the laws and regulations. It needs to be determined whether these grids are publicly or privately owned and operated. These grids need to be safely operated and designed

and the actors connected to the grid need to be protected. The challenge is to determine under what conditions these grids could be operated and designed.

4. The injection regime of natural gas is stated in the energy codes. In the public grids a connection obligation is active but not a transportation obligation. The challenge is to determine whether this injection regime is an adequate regime to accommodate large volumes of locally produced hydrogen in the distribution grids.
5. It needs to be determined what hydrogen production activities are desirable and which entities can enter the market for production. The challenge is to efficiently regulate the access of the entities for the various hydrogen production activities.
6. The tariff-structure for hydrogen is not defined yet. The challenge is to determine how the tariff structure of hydrogen should be built up.
7. Industry standards need to be formed.

#### **Coordination – Economic-institutional**

1. The modes of organization need to be formulated regarding the security of supply. The challenge is to determine if the modes of organization need to change and how.
2. The monitoring and control of the hydrogen activities will be dependent on the formulation of clear laws and regulations. A supervisory body needs to exist that monitors and controls these laws and regulations. The challenge is to first formulate the laws and regulations and hence organized the monitoring and enforcement.
3. When hydrogen is largely produced on a local level, the DSOs get a more intensive balancing role. The challenge is to determine what is needed to allow for such a role and what modes of organization are needed to perform such a role.

## 9.8 Interview Dr. T.W. Fens – Associate Partner at Deloitte B.V. and senior research fellow at TU Delft

Date: 22/02/2019

### Summary of interview

#### Paris agreements

- Every EU member state needs to reduce its CO<sub>2</sub> emissions according the Paris agreements. The reductions can be accomplished in several sectors.
- The electricity generation sector needs to use sustainable alternatives to fossil fuels.
- The transport sector needs sustainable alternatives to petrol.
- The stationary end-use applications in the industry and smaller the smaller scale consumption segments need to be based on sustainable alternatives (i.e. alternatives that mitigate the CO<sub>2</sub> emissions).
- The built environment hence needs to integrate an alternative to natural gas.

#### Replacement of natural gas in the built environment

- District heating is an option.
- Geothermal energy is an option.
- All-electric is an option.
- The replacement of natural gas for a sustainable gas in the existing gas grid is an option (i.e. replacing natural gas by hydrogen, biomethane or synthetic methane).

#### Natural gas infrastructure needs to be adjusted to be compatible with hydrogen

- Current compressors are not functioning anymore.
- The gas flow rate needs to increase.
- Metering installations need to be replaced.
- End-use equipment needs to be replaced for alternatives.
- Seals need to be replaced.
- Hydrogen needs to be produced.

#### Hydrogen as a substitute for natural gas

- The production of green hydrogen is dependent on the surplus of renewable electricity.
- Hydrogen is a proper substitute for natural gas and mainly in dense urban areas with an extensive gas infrastructure.
- Hydrogen will be transported both on the transmission and distribution level. Technically the pipeline transport of hydrogen is not a problem.
- The transition from a natural gas network to a hydrogen network is an issue of costs and manageability. The technical hurdles are not the key issues.
- Hydrogen production will get a centralized character since large volumes of hydrogen need to be produced. These production facilities need to be sited.
- Hydrogen will be introduced gradually. The full hydrogen production capacity to replace the natural gas demand of the distribution grid connections does not need to be available immediately.

#### Dutch climate agreement and regional energy strategies

- Hydrogen will play a significant role in both the Dutch climate agreement as the energy strategies. Hydrogen can be used to store the surplus of renewable electricity. With the extensive Dutch natural gas infrastructure, hydrogen becomes a viable option to replace natural gas and to accommodate the potentially large renewable electricity surplus in the future.

### **Costs of energy transitions**

- The costs of the transition towards alternative energy sources reflect the costs of the CO<sub>2</sub> emissions.

### **System architecture**

- Hydrogen will be produced centrally based on large-scale electrolysis.
- The decentralized production of hydrogen will also play a vital role in the storage of the surplus of renewable electricity that cannot be injected in the local electricity distribution grids. The decentralized production technologies are not new, they already exist.
- It is hence likely that the decentralized production of hydrogen will occur. The decentralized production of hydrogen will be based on the surplus of decentralized produced electricity. The main advantage is that the electricity grid does not need to be scaled up when hydrogen can be produced and stored locally (i.e. on decentral level).
- These decentralized hydrogen production and storage facilities can be collectively installed by neighborhoods.

### **The transition to hydrogen**

- The difficulties in a transition to hydrogen are not necessarily in the hydrogen production, transportation, and end-use technologies that need to be integrated. The understandings on the physics of hydrogen gas are also not a main issue, the potential threats of integrating hydrogen are hence known.
- The issues of integrating hydrogen as an energy carrier in the built environment are in the acceptance of the public, the costs, and the institutional arrangements that need to be adjusted.
- Chances are especially required in the institutional environment and the governance structures applicable to the natural gas infrastructure.
- In the transition to hydrogen end-use equipment. Gas condensing boilers can be replaced partly by fuel cell systems that generate both heat and electricity. These fuel cell systems are currently working on natural gas with reformers to separate the hydrogen as input for the fuel cell. When the natural gas grid connections at the consumer are replaced by hydrogen grid connections, these systems still function. Only the reformer became a redundant part. Such an implementation can enhance the transition to hydrogen in the built environment.

### **Applicability of laws and regulations to hydrogen**

- Laws and regulations around natural gas are extensive. It is important to identify whether the laws and regulations are applicable to a hydrogen infrastructure or not. When hydrogen is integrated, the laws and regulations applicable to the gas infrastructure need to be compatible with the use of hydrogen.
- The current institutional arrangements and governance structures should be enriched for the use of hydrogen as an energy carrier. The justification of changing these laws and regulations needs to be solidly formulated and transparent.
- It needs to be clear that the challenges of integrating hydrogen are manageable. The communication about the justification of the costs and the safety issues is important.

### **Network topology**

- It is important to consider which parts of the natural gas grid will be converted to hydrogen grids.
- The natural gas extraction in Groningen is declining and hence the supply of G-gas is declining. It is important to start somewhere, the production and storage facilities in Groningen can be a suitable starting point.
- End-use equipment of hydrogen can be based on fuel cells that both generate heat and electricity. The latter implies that the heat and electricity supply of the built environment become more

integrated. Fuel cells can mainly be used in the winter, when the yield of renewable electricity is lower, to overcome possible shortages.

- It is important to gradually transform the gas grid to a hydrogen grid.
- The need for hydrogen at the end users in the built environment is the highest.

### **Production capacity**

- Blue hydrogen will play a key role in the transition towards green hydrogen. Natural gas will stay available for a reasonable price. The advantage of blue hydrogen is that the transition of the infrastructure can already start. When large production capacities of green hydrogen become available than can be gradually integrated in an existing system.
- The development of large-scale and cost-effective electrolyzers is currently underway.
- Production activities should be regulated in terms of safety and gas qualities.
- A natural gas well requires a constant production rate to adequately operate the facility. When the production rate is volatile, problems can occur in the operation of the wells.
- The production of green hydrogen can be relatively easy by scaled up and down.

### **CCS**

- CCS will be a short-term solution for the CO<sub>2</sub> emissions and will be redundant when enough green hydrogen production capacity is installed.

### **Unbundled supply chain**

- Currently the supply chain of natural gas is organized in a way that the transport of natural gas is facilitating the market functioning of both the wholesale and retail market. These public grids safeguard the public service character and the safety of the gas provision.
- There is no need to change the supply chain model that is currently applicable because of the integration of hydrogen. Hydrogen producers will become less dependent on mining activities and can hence operate more like the electricity producers.

### **Operational coordination**

- The technology to utilize hydrogen is already available, it is mainly an issue of the laws and regulations applicable to the provision of gas.
- The technical codes for gas need to be adjusted to be compatible with hydrogen.
- Metering installation to measure volumes need to be adjusted to be compatible with hydrogen.
- Safety requirements need to be reformulated since hydrogen has other properties than natural gas.

### **Storage of hydrogen**

- The question is if depleted gas reservoirs will be used for the underground hydrogen storage. The large-scale storage of hydrogen will be necessary and depleted gas reservoirs can play a key role. The main issue is that hydrogen can get contaminated by the compounds and liquids that are present in the depleted gas reservoirs. Hydrogen hence needs to be cleaned from these impurities when it is to be consumed in the end-use equipment compatible with specific hydrogen gas standards.
- Salt caverns are suited to store hydrogen but are relatively small, compared to depleted gas reservoirs.
- Salt caverns can be constructed but are dependent on the geographical existence of salt layers. These layers are not existing throughout the country and are mainly concentrated in Groningen.
- The storage of hydrogen needs to address, short-term storage demand, mid-term storage demand, and long-term storage demand.
- Short-term storage capacity will be locally organized. Mid-term and long-term storage demand can be covered by the storage in salt caverns, depleted gas reservoirs, through liquified hydrogen in vessels, or through hydrides.

- The transport and storage systems need to function in such a way that the production and consumption of hydrogen over the short and long-term is in balance.
- Storage is both on the transmission as on the distribution level essential.

### **The energetic efficiency**

- With a large renewable electricity supply, the viewpoint of energetic energy efficiency regarding the use of hydrogen changes to the issue of availability. Currently it can also be concluded that not converting solar or wind energy electricity or hydrogen is inefficient.

### **Access regulation**

- Can be arranged like the natural gas infrastructure is arranged.

### **Hydrogen market**

- The natural gas market is already functioning with MWh (i.e. energy content). It is hence irrelevant if the energy content is supplied by natural gas or hydrogen.
- In analogy with natural gas, a bilateral market and a spot market can exist for hydrogen. The volumes of hydrogen that are traded can present in the grid and in the various storage possibilities.
- The market could include new transactions in the form of conversion capacity. The transportation capacity is hence only linked to a certain gas standard and volumes, The MWhs of gas that are traded can be in any form.

### **Tariff structure**

- The government can help the emergence of hydrogen production capacity with lower taxes to make it compatible with natural gas.
- Currently hydrogen is more expensive than natural gas. This can be changed with a proper tax structure.

### **Transactions**

- No barriers, only the energy carrier changes. The same mechanism that already exist can be used for hydrogen.

### **Horizontal and vertical integration**

- The supply chain consists of the segments: production, wholesale market, transmission, distribution, metering, and retail. Production, wholesale market, metering, and retail are coordinated through a market. Distribution and transmission are state regulated.
- Storage can be both publicly and privately coordinated.
- Transmission and distribution activities are subject to different institutional environments.

## **Changes positioned within Comprehensive Design Framework**

### **Changes in the technical-operational dimension**

#### **Access**

#### **System architecture**

- The production of green hydrogen is dependent on the surplus of renewable electricity generation. This implies a change in the nature of the gas production due to the availability of renewable electricity surplus compared to the extraction of natural gas from the gas reserves.
- The centralized production of hydrogen will be dominantly be based on electrolysis. The electricity and gas infrastructures will hence operate more intertwined.

- The decentralized production of hydrogen will also play a key role. Especially when the renewable electricity cannot be injected in the public grids. The introduction of more decentralized production will change the system architecture. The electricity and gas system become more closely interrelated.
- Because of the decentralized production of hydrogen, storage facilities will also emerge on a decentral level. Currently storage facilities merely exist on a central level (i.e. on a large-scale) and are operated by a small number of mining companies. The decentralized storage facilities can be operated by many storage operators in a variety of different forms and capacities.
- End-use equipment in the built environment can largely be based on fuel cell technologies that generate both heat and electricity. This would change the nature of the system architecture since the gas system would deliver the electricity, heat, and gas demand.
- The storage of hydrogen will become more dependent on the need to store the renewable energy surplus instead of the need to accommodate the slowly changing production rates of the gas fields. The main purpose of storage will still be to match the production and consumption of gas on both the short and long-term but with another nature of production.
- CCS infrastructure need to be integrated in the gas infrastructure to realize the production of blue hydrogen.
- The system architecture can be much more designed based on the availability of renewable electricity when it is converted to a hydrogen-based architecture. The issue of energetic efficiency becomes less relevant when enough green hydrogen can be produced.

#### **Asset characteristics**

- Seals need to be replaced.
- The compressors used in the transmission and distribution systems are not compatible with hydrogen and need to be replaced or adjusted.
- The gas flow rate of hydrogen in the gas infrastructure needs to increase to transport the same energy content as with natural gas.
- Metering installations need to be replaced to handle the larger gas flow rates of hydrogen.
- End-use equipment needs to be replaced for end-use equipment compatible with hydrogen.

#### **Responsibilities**

##### **Network topology**

- More producers will be entering the gas sector both on a central as on decentral level because of the nature of the hydrogen production. More gas entry points can be necessary. The integration of more entry points will change the nature of the interaction between the production segment and the storage, transmission, distribution, and end-use segments.
- In the transition of the gas grid to a hydrogen grid it is important to determine which parts of the grid will be transformed and when these parts will be transformed. The transformation implies the transformation of all the assets, and entry and exit points present in the specific part of the grid. When parts of the Dutch gas grid are using hydrogen and other parts natural gas this requires other interactions to occur between the various nodes and links of the system.

##### **Production, grid, and storage capacity**

- Blue hydrogen will play a key role in the transition towards green hydrogen. Large volumes of hydrogen need to be produced from natural gas.
- The production of green hydrogen will be dependent on large-scale electrolyzers that need to be installed. The energy input of the green hydrogen production will come from renewable electricity. The availability of the latter energy input is much more volatile than the availability of natural gas. This can change the requirements of the installed production and storage capacity that is needed to satisfy the demand for hydrogen.
- The production of green hydrogen is more convenient to manage in terms of output compared to the natural gas extraction. This can change the requirement for storage.



- Hydrogen storage on the short-term will be dependent on locally organized storage facilities. The mid to long-term storage will be conducted through the underground storage of hydrogen in depleted gas reservoirs and salt caverns, the liquified storage of hydrogen, or through storage in hydrides. The decentralized storage of gas will become more important than it currently is with natural gas due to the decentralized production of hydrogen.
- Storage will both be conducted at the transmission and distribution level.

### **Redundancy planning**

#### **Ownership and decision rights**

- Ownership and decision rights of hydrogen production plants can be much more like the electricity producers.

#### **Coordination**

##### **Operational coordination**

- Need to be changed to be adequate for the use of hydrogen, will not be problematic.

##### **Routines, emergency procedures, and preventive maintenance**

- Need to be changed due to the properties of hydrogen but will not be problematic.

#### **Changes in the economic-institutional dimension**

##### **Access**

##### **Competition and state intervention**

-

#### **Responsibilities**

##### **Sector laws and regulations**

- The natural gas sector laws and regulations need to be changed to be applicable to the use of hydrogen as an energy carrier.
- The technical codes need to be adjusted to be compatible with hydrogen.
- Safety laws and regulations need to be reformulated to be applicable with the properties of hydrogen.

##### **Access regulation**

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##### **Tariff regulation**

- Hydrogen will become more expensive than natural gas. The taxes on the various energy carriers can be used to compensate these differences and indirectly implement a CO<sub>2</sub> tax.

#### **Ownership and decision rights**

- Hydrogen production activities should be regulated in terms of safety and the gas qualities that are injected in the public grids. New gas standards need to be introduced in the energy codes and regulations on gas qualities. The safety requirements of the production activities need to be standardized and adopted in the laws and regulations.

#### **Spot market rules**

- The market could include a hydrogen market where hydrogen is traded per kWh in the same way as natural gas is currently traded. Hydrogen gas is changed in the market per kWh, the spot

market rules and regulations applicable do not need to change significantly. It could be possible that the balancing mechanism and the damping formula need to be changed.

- Conversion capacity of electricity to hydrogen or vice versa could also be traded on the market.

**Industry standards**

1. Industry standards need to be formulated for hydrogen. The existing natural gas standards can be adjusted to be applicable with hydrogen.

**Coordination**

**Contractual arrangements and modes of organization**

-

**Horizontal and vertical integration**

2. Storage can both publicly and privately coordinated.

**Principal-agent and opportunistic behavior safeguards**

-

What challenges are there?

	<b>Technical-operational</b>	<b>Economic-institutional</b>
<b>Access</b>	11. The system needs to allow for the interaction with a variety of producers both centralized as decentralized. 12. The nature of the interaction between the electricity and gas infrastructures changes. 13. The system needs to allow for the interactions with new storage facilitators both on a centralized and decentralized level. 14. The large-scale integration of the decentralized production of hydrogen changes the interaction between distribution and transmission grids.	16. The production segment will become more competitive.
<b>Responsibilities</b>	16. The production of green hydrogen is dependent on the availability of renewable electricity surplus. 17. The production of hydrogen is dependent on the existence of CCS infrastructure. 18. Specific locations connections between gas and electricity infrastructure. 19. Decentralized hydrogen injection.	25. Hydrogen transport through public grids. 26. The role of the distribution grid operator when large volumes of hydrogen are injected in the distribution grid. 27. Ownership and decision rights regarding the hydrogen production facilities need to be formulated.

	20. The end-use equipment in the built environment needs to be replaced.	28. Considering the hydrogen system cost in tariff structure of various energy carriers. 29. Formulation of new gas standards. 30. The end-use equipment in the built environment needs to be replaced.
<b>Coordination</b>	8. The supply fluctuations will differ from the natural gas extraction.	9. Mechanisms that ensure that the production capacity is adequate. 10. Organization of decentralized injection.

### Explanation of the challenges

#### Access – Technical operational

1. The nature of the gas production changes since the hydrogen production does no longer include mining activities. The production of hydrogen becomes a conversion process where hydrogen can be produced from a variety of different energy sources at various locations. A larger number and larger variety of hydrogen producers can emerge that vary in location, the gas quality that is produced, and the supply that they want to inject in the distribution or transmission grids. The system architecture needs to adopt a wider variety of different gas producers. It is challenging to both technically and organizationally coordinate the operation and allowance of these new producers. The gas qualities and volumes that are injected in the grids need to be monitored and controlled. The grids need to be suited for the interaction with more entities at more entry points. The distribution grids in special are currently predominantly supplied by the transmission grid. When many producers want to inject hydrogen in the distribution grids (i.e. interact with) new technical operational and organizational requirements need to be addressed.
2. The production of green hydrogen (i.e. the conversion of electricity to hydrogen) and the possibility of hybrid end-use equipment (i.e. both functioning with electricity and gas) make the electricity and the gas infrastructure to be more interwoven. Electricity can easily be converted to hydrogen and vice versa. The challenge is to determine de how both system architectures can be interconnected and what is desired.
3. With the emergences of decentralized production facilities and the availability of a local renewable electricity surplus, the demand for local hydrogen storage also emerges. These storage facilities need to be integrated in the existing system architecture. The challenge is to determine whether the current system architecture is suitable for the integration of a larger number of decentralized storage facilities.
4. With the decentralized injection of high volumes of hydrogen, the distribution grids will become less dependent of the gas supply from the transmission grid. The latter will change the interaction between both systems. The distribution system architecture will include more entry points and exit points that are necessary to connect new storage operators and producers. The challenge is to determine whether the distribution grids are technically suitable to fulfill such a function and to what degree. These developments will be like the developments of the decentralized production and injection of biogas.

#### Responsibilities – Technical operational

1. The production of green hydrogen is dependent on the installment of renewable electricity generation capacity. Moreover, it is likely that only the renewable electricity surplus will be used to produce hydrogen. To achieve enough green hydrogen production capacity on the short-term is challenging. Blue hydrogen is hence easier to integrated on the short-term and will probably function as an intermediate to allow the green hydrogen production capacity to increase.

2. The production of blue hydrogen implies the inclusion of CCS in the hydrogen production process. CCS infrastructure needs to be constructed and accepted. The latter is challenging since no CO<sub>2</sub> storage is yet conducted in the Netherlands.
3. The production of hydrogen is basically a conversion process just like the generation of electricity. It is important to determine which entities (i.e. public or private) can participate in these conversion processes. Since the green hydrogen production will largely be dependent of the renewable electricity surplus, the conversion from electricity to hydrogen becomes important. It is a challenge to determine where the conversion capacity needs to be sited and who operates and owns this capacity. Hydrogen production capacity is basically conversion capacity. The question is how the laws and regulations will address the various conversion processes that can be applicable.
4. When large volumes of hydrogen are injected on the level of the distribution grids, the DSOs get a more intensive balancing role. It is challenging to determine if the network topology of the distribution grids need to change or if transport capacities need to increase (i.e. capacities in volume and booster capacity).
5. The current natural gas condensing boilers need to be replaced by boilers compatible with hydrogen or by fuel cell heating systems and metering installations need to be adjusted. The challenge is to replace the natural gas condensing boiler for a safe and adequate alternative.

#### **Coordination – Technical operational**

1. The supply of natural gas is currently largely dependent on the inland extraction of natural gas and the imports. The production of biomethane or synthetic methane is rather small. The production of hydrogen is a conversion process that can be dependent on a variety of energy sources, including natural gas. To produce green hydrogen, biomass and renewable electricity are used as energy input. The production of hydrogen will hence follow another supply profile compared to the production of natural gas. It is challenging to determine how the operational coordination of the system needs to change to match the supply profile with the demand profile.

#### **Access – Economic-institutional**

1. The production segment of hydrogen will become more competitive since the natural entry barriers included in the mining activities do not exist anymore. Important is to consider where competition is possible and how hydrogen will be produced by who (i.e. public or private)

#### **Responsibilities – Economic-institutional**

1. The system operators are currently not allowed to transport hydrogen through their pipeline networks. The gas Act and the energy codes need to be adjusted to allow the grids to operate with hydrogen as an energy carrier.
2. When large volumes of hydrogen are injected on the level of the distribution grids, the DSOs get a more intensive balancing role. It is challenging to determine how the role of the DSO will change with an increasing amount hydrogen injected in the distribution grids.
3. The production/ conversion of hydrogen will be new within the gas infrastructure. It needs to be defined whether the ownership and decision rights are publicly or privately owned. Laws and regulations need to be formulated for the latter. A challenge is to determine where the conversion/ production of hydrogen will take place and which parties can be involved in these activities where.
4. The costs of a transition to a hydrogen infrastructure require large up-front investments in all segments of the value chain. Laws and regulations need to consider if these costs need to be socialized or not and how these investments can be incentivized. The socialization of these costs implies a large degree of state intervention. Market mechanisms to ensure the investments are also possible. The challenge is to formulate a proper framework for the investment in hydrogen production, storage and transportation capacity and simultaneously

stimulate the hydrogen demand. The variations in tariffs of natural gas and electricity (i.e. grey, blue, and green tariffs) can play a role.

5. New gas standards need to be formulated that are applicable throughout the entire system. These gas standards need to be formulated by the government and stated in the laws and regulations. These standards should be monitored and controlled by the system operators. The challenge is to formulate the appropriate gas standards for the various parts of the pipeline networks.
6. The current natural gas condensing boilers need to be replaced by boilers compatible with hydrogen or by fuel cell heating systems and metering installations need to be adjusted. The challenge is to formulate laws and regulations that allow for the replacement. Moreover, standards and certificates need to be established for the equipment and the installation of the equipment.

#### **Coordination – Economic-institutional**

1. Currently the exploitation of the Dutch natural gas reserves is highly regulated by the State. When hydrogen can be produced from a variety of sources and the Dutch natural gas extraction declines, other mechanisms should be in place to ensure the investments in the production/import capacity adequacy.
2. The decentralized injection of hydrogen requires, in analogy with the biogas injection, agreements in terms of the capacity that can be injected entry points and the investments that can be made to connect the producers to higher-pressure grids. This challenge exists for the DSOs, and partly in the formulation of the laws and regulations applicable to the access regulation of the producer segment.

## 9.9 Interview Prof.dr.ir. Z. Lukszo – Full professor at TU Delft, Engineering Systems and Services

Date 18/02/2019

### Summary of interview

#### Centralized hydrogen production

- The centralized production of hydrogen should be based on electrolysis. Offshore wind farms should produce the electricity necessary as the energy input for the electrolysis process.
- Electrolysis is the most important hydrogen production technology since it is the only hydrogen production process adequate to produce green hydrogen.
- The large-scale offshore hydrogen production is efficient in terms of system costs.
- It is important to determine where the hydrogen production facilities will be sited. The offshore production of hydrogen is preferable and implies the transportation of hydrogen through pipelines from the offshore production facilities to the onshore pipeline networks (i.e. transmission and distribution grids).
- Hydrogen production facilities are less dependent on a geographical location compared to the production of natural gas.
- It is technically possible to place large electrolyzers (i.e. including large production/converting capacities) to produce hydrogen. The challenge of realizing these large-scale electrolyzers to satisfy the demand for heating the built environment is mainly a challenge of costs.
- As a result of a learning curve in the production of hydrogen from electrolysis, research indicates that on the short-term the hydrogen production costs can be reduced to 2 €/kg.
- The hydrogen production costs from wind energy can be further reduced if the price of electricity from wind is low (i.e. due to high availability rate).
- Hydrogen can be imported from production sites where the production costs are relatively low (i.e. locations with high availability of renewable electricity generation).
- Production of hydrogen based on electrolysis can also be considered a conversion process instead of a production process. The hydrogen conversion processes include lower tax tariffs compared to the production tax tariffs. The latter could incentivize producers to enter the production/conversion of hydrogen based on electrolysis. This should be addressed by the laws and regulations applicable.

#### Decentralized production

- The decentralized production of hydrogen through electrolysis will also play a vital role in the future.
- When many decentralized producers are active it is important to have adequate technical control mechanisms in place. Pressure levels, gas qualities, and directions need to be controlled. Coordination is also necessary on the organizational level.

#### Mix between centralized and decentralized hydrogen production

- Natural gas is produced highly centralized. A future hydrogen infrastructure will rely both on the centralized and decentralized production of hydrogen.
- The coordination between a decentralized system of production and a centralized system of production is essential. The interaction between the coordination of these systems is new and a relevant challenge.

#### Asset characteristics

- The materials used in the transmission and distribution networks need to be replaced/adjusted to be compatible with the transportation of hydrogen.
- The compression and metering stations need to be adjusted to function with higher gas flow rates of hydrogen.

### **Network topology and coordination**

- Technically, the network needs proper mechanisms to control the pressure levels, the gas qualities, and the gas flow.
- Organizationally, the network also needs proper coordination mechanisms to reach system efficiencies.
- It is important to determine how the current network topology is suitable for the centralized and decentralized production of hydrogen.
- Important questions are:
  - Which locations in the gas grid are suitable for the injection of natural gas?
  - And how to coordinate the injection of natural gas?

### **Underground hydrogen storage**

- It is important that Dutch laws and regulations address the underground storage of hydrogen. Requirements for the storage operators and the actual storage activities need to be formulated.
- Should be privately owned but with adequate access and tariff regulations.

### **Hydrogen transport**

- Should be publicly owned and operated.
- Transportation tariffs (transmission and distribution) and access to the capacity should be regulated for hydrogen transportation networks.

### **Public versus private ownership**

- It is important that the government determines whether the production, storage, transmission, and distribution segments of a hydrogen infrastructure will be publicly or privately owned and operated.

### **Standardized hydrogen gas qualities**

- The hydrogen gas qualities should be standardized based on the end-use applications.
- Industrial end-use applications might use other qualities than residential and service sector end-use applications. Fuel cells might also need other qualities than hydrogen condensing boilers.
- Hydrogen producers are responsible to produce hydrogen in the right qualities from the grid that the hydrogen is injected in. The latter should be monitored and controlled by the system operators of the grids.

### **Standardization of the technological properties is necessary**

- The hydrogen gas qualities, operational pressures, asset characteristics, and temperatures need to be standardized to achieve a reliable and robust system performance.

### **Operational coordination**

- Technical control mechanisms should be adjusted to be compatible with hydrogen.
- Routines, emergency procedures, and preventative maintenance activities should be adjusted to the new requirements of the use of hydrogen.

### **Competition and government intervention**

- Transmission, distribution, and storage need a certain degree of governmental interference.
- Production should be privately owned and operated. The government should hence only control and enforce competition law to safeguard public values as fair prices and access.
- Market parties have the expertise to produce hydrogen. A well-functioning market in the production of hydrogen can generate public benefits in terms of costs.

### **Wholesale and retail market**

- A retail market on the level of the distribution grids will be an elegant solution when hydrogen is produced largely decentralized.
- Important is how to connect the functioning of both a wholesale and retail market when large volumes of hydrogen are available at the level of the distribution grids.

### **Access regulation**

- The production segment of hydrogen should be open to everyone who wants to produce hydrogen. Regulation should be dependent on the application and the scale of the hydrogen production and should address the safety issues. It is desirable that no strict access regulation is applicable to the production of hydrogen.
- When hydrogen is injected in the transmission and distribution grids, access should to these grids should be regulated.
- The transmission and distribution activities should be regulated and performed by public entities (i.e. public system operators). This is important since the transmission and distribution systems should efficiently deliver hydrogen in a non-discriminatory fashion.
- The storage of hydrogen could also be conducted by private actors. This should be regulated based on the safety and economic requirements.
- Access to the markets should be open and regulated based on certain prerequisites based on competence in terms of expertise and financially. A public body should assess these prerequisites and approve the access.

### **Tariff regulation**

- The market should determine the price of the volumes of hydrogen.
- The transport capacity tariffs should be calculated within the regulatory boundaries determined by the regulator (i.e. ACM).
- The storage capacity tariffs can be regulated in a similar fashion as the transportation capacity tariffs.
- Investments in production and storage capacity need to be viable based on the tariffs for the production, transportation, and storage of hydrogen. The tariff regulation is hence important in achieving enough production and storage capacity.

### **Large scale investments in hydrogen production and storage facilities**

- The large-scale investments in hydrogen production and storage facilities require high and specific investments. These investments should be organized in a way that protects the investing companies and the public values.
- Potential hydrogen producers and storage operators should be incentivized to invest in production and storage capacity. Without an adequate investment environment for potential producers and storage operators, a hydrogen infrastructure is impossible to emerge.

### **Ownership and decision rights**

- The production of hydrogen is owned and operated by private companies.
- The transmission and distribution grids are publicly owned and operated based on the notion that everyone should have access to the grids in a non-discriminatory fashion. The operation of the grids should also be based on the public service obligation instead of the most cost-efficient operation.
- Storage facilities should be owned and operated by private companies. Mechanisms should be in place that ensure that enough storage is available to meet the public service obligations. Actors should have access to the storage facilities on a non-discriminatory basis.
- End-use applications are privately owned. Micro-grids (i.e. grids that are owned and operated by for example energy collectives) can also be seen as end-use applications of the larger hydrogen grids owned and operated by the regular TSO and DSOs.



### **Industry standards**

- Industry standards should be determined through the standardization authorities on the European level in collaboration with the national standardization authorities.
- European hydrogen standards are preferable. A hydrogen economy is highly intertwined with the electricity sector. In analogy with the electricity sector, a hydrogen sector would also require a European approach.
- Technological standards should be determined on a European level. The tariff standards should be determined on a national level.

### **Modes of organizing transactions**

- Volumes of hydrogen should be transacted in a market.
- Storage services should be transacted bilaterally between the storage operators and other shippers.
- Transportation capacity should be transacted in a similar fashion as it is currently transacted.
- Storage capacity adequacy and production capacity adequacy investments should be incentivized by the government. This is mainly important in the beginning of a transition to hydrogen (i.e. important for the investments that are needed on the short term). Subsidies might be necessary. Collaboration between the sector and the government is hence essential.
- For the long-term, a proper framework should be developed that ensures the investments in production and capacity adequacy that relies less on the support of the government.

### **Vertical and horizontal integration**

- Basically, hydrogen transmission and distribution grids should be publicly owned and operated.
- The production, storage, and end-use segments should be privately owned and operated. The government should only interfere to safeguard safety issues and discriminatory situations.

### **Supervisory bodies**

- Should have a public supervisory body that monitors and controls the operational activities regarding hydrogen in terms of the laws and regulations applicable on safety, standards, etcetera.
- The ACM should monitor and control whether access to hydrogen can be gained in a non-discriminatory fashion. Moreover, ACM should enforce the competition law.
- How many DSOs and TSOs are necessary? What is desirable and why?

## Changes positioned within Comprehensive Design Framework

### Changes in the technical-operational dimension

#### Access

#### System architecture

- The production locations of hydrogen gas will differ from the production locations of natural gas. This refers to the notion that the production of hydrogen is not dependent on the natural gas extraction but on the availability of renewable electricity.
- The hydrogen production facilities will be sited next to the locations of the renewable electricity generation. Wind farms, especially offshore, will produce the main share of the future renewable electricity in the Netherlands.
- Imports of hydrogen gas from areas with low renewable electricity prices will become more important (i.e. due to the higher wind energy and solar panel yields at specific locations).
- The decentralized production of hydrogen will change the technical system architecture. The centralized production facilities will not be sited at the natural gas wells. Moreover, many producers that produce smaller volumes of gas can enter the production segment. The larger number of producers in a variety of locations need to inject the produced hydrogen gas into the national grid. A mix between centralized (i.e. large scale) and decentralized (i.e. smaller scale) production facilities would require other interactions to occur between the producers and the system than in the highly centralized natural gas production. Next to the interactions with the new producers of hydrogen and the national grid, storage operators will also emerge next to the new locations of the hydrogen supply. The interactions between storage operators, producers, and the national grid will change.
- Storage facilities need to be sited nearby the hydrogen production facilities for efficiency purposes.
- A future hydrogen infrastructure is highly intertwined with the electricity infrastructure.

#### Asset characteristics

- The asset characteristics of the whole natural gas supply chain must be adjusted to be compatible with the new gas quality and gas pressure standards.
- The production of hydrogen from electricity will be less flexible as the production of natural gas. No electricity reserves are available as with the natural gas reserves.
- Small-scale end-users can also utilize fuel cells and heat pumps to generate heat instead of a hydrogen condensing boiler.
- Storage facilities need to be adjusted to be compatible with hydrogen. New storage facilities need to be built (i.e. salt caverns).

#### Responsibilities

#### Network topology

- The existing natural gas grid topology is designed to transport the centralized produced and stored natural gas to the customers unilaterally. With the integration new hydrogen production technologies, the suitability of the network topology to integrate many producers at other locations should be investigated.
- Entry points in the national gas grid need to be reallocated or need to be added because of the changing production, storage, and import characteristics.
- When the decentralized production of hydrogen needs to be injected in the distribution grid, it should be investigated whether these network topologies are suitable for the injection at various places (i.e. instead of the injection from the transmission grid).

#### Production, grid, and storage capacity

- The production capacity should be based on the capacity to produce green hydrogen.

#### Redundancy planning

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### **Ownership and decision rights**

- Hydrogen production facilities should be privately owned and operated.
- Storage facilities should be privately owned and operated.

### **Coordination**

#### **Operational coordination**

- Technical control mechanism should be adjusted to be compatible with hydrogen.

#### **Routines, emergency procedures, and preventive maintenance**

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### **Changes in the economic-institutional dimension**

#### **Access**

#### **Competition and state intervention**

- Production should be privately owned and operated. A better functioning market in the production segment can result in lower production costs.
- A retail market on the level of a distribution grid can be an elegant solution. This would make the coordination between the wholesale and retail market essential. Currently, no retail market exists for producers.

### **Responsibilities**

#### **Access regulation**

- The access regulation of the production of hydrogen should be dependent on the application and the scale of the hydrogen production. No strict access regulation should be applicable. Permits to produce natural gas are well specific. Permits for hydrogen can extent the constraints of the number of wells and more producers can be allowed.

#### **Tariff regulation**

- Large investments need to be made in the hydrogen production and storage facilities. The tariffs of hydrogen should include a mechanism to earn back the large investment costs.

### **Ownership and decision rights**

- The ownership and decision rights of the production of hydrogen should be privately owned.

### **Spot market rules**

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### **Industry standards**

- Technological industry standards should be made on the European level. Tariff standards on the national level.

### **Coordination**

#### **Contractual arrangements and modes of organization**

- Volumes of hydrogen should be transacted in a market. This would imply that a market in the retail supply needs to emerge or smaller-scale consumers should be able to buy hydrogen from the wholesale market.
- Investments in storage and production capacity should be incentivized by the government. This is mainly important in the beginning of the transition but stays important on the long-term. Especially looking at the different availability characteristics of green hydrogen.

### Horizontal and vertical integration

- Transmission and distribution activities should be publicly performed.
- Other activities are free to participate in.

### Principal-agent and opportunistic behavior safeguards

- A supervisory body needs to be appointed to monitor and control the hydrogen production. The monitoring and control of the injection of hydrogen will become more important when the number and variety of producers increases.

What challenges are there?

	<b>Technical-operational</b>	<b>Economic-institutional</b>
<b>Access</b>	15. Large-scale LH <sub>2</sub> imports from neighboring countries. 16. Degree of centralized and decentralized production. 17. Matching the hydrogen infrastructure with the electricity infrastructure.	17. Formulation of formal European and national hydrogen laws and regulations. 18. Retail market.
<b>Responsibilities</b>	21. Siting of the hydrogen production plants. 22. Siting of the hydrogen storage facilities. 23. Allocation of entry points in transmission and distribution grid. 24. Applicability of grid design for decentralized production and injection. 25. Hydrogen production capacity shortage. 26. Hydrogen storage capacity shortage.	31. No hydrogen Act. 32. Access regulation on the production of hydrogen needs a different approach. 33. Tariff regulations should include the need for large-scale investments. 34. New industry standards need to be formulated (i.e. in Europe and nationally).
<b>Coordination</b>	9. A supervisory body must exist that monitors and controls the production of hydrogen. 10. A supervisory body must exist that monitors and controls the storage of hydrogen. 11. Control mechanism, routines, emergency procedures, and preventive maintenance activities need to be tested and adjusted.	11. Storage and production capacity adequacy mechanisms. 12. ACM needs to adopt hydrogen codes and permitting procedures.

### Explanation of the challenges

#### Access – Technical operational

1. In the future when renewable electricity can be cheaply produced at specific locations due to the higher yields involved, it will be desirable to transport the energy. The energy supply in those specific production areas is higher than the demand. Electrolysis will be a solution to efficiently store and transport the energy surplus to areas of demand in the form of hydrogen.

An efficient way to transport the hydrogen is in large ship tankers. When the national supply of hydrogen will become largely dependent on the imports of hydrogen, the system architecture of the Dutch natural gas grid needs to be suited to inject large volumes of hydrogen from imports.

2. The degree of centralized and decentralized production of hydrogen determines to a large extent how the system needs to be operated and designed. A fundamental challenge is to determine to what extent the decentralized production of hydrogen will be allowed. For various degrees of the diffusion of the decentralized production technologies, the system architecture must be designed and operated differently. It is important to investigate to what degree the current system architecture is applicable to the integration of more decentralized forms of gas production.
3. The production of green hydrogen will become important to reduce the dependency on fossil fuels and especially on natural gas. When hydrogen needs to be entirely produced from electrolysis for the total distribution grid demand (i.e. to replace approximately 20 m<sup>3</sup> of natural gas), approximately twice the total Dutch annual electricity supply is necessary. It is important to consider how a hydrogen infrastructure will interact with the electricity infrastructure.

### **Responsibilities – Technical operational**

1. The siting process of the hydrogen production plants will be a challenge. Many determinants such as the energy input availability, the available transportation infrastructure, and the technical-operational boundaries of the Dutch gas grid play a role in the siting process. The siting process is constrained by the current possibilities of the grid. The possibilities of different scenarios should be investigated.
2. The siting process of the underground storage facilities is, in analogy with the production facilities, also constrained by the possibilities of the existing gas grid. However, the underground storage facilities are more dependent on the specific geographical locations.
3. When more producers of hydrogen are connected to the grid this might pose problems for its operational functioning. It needs to be determined whether entry points can be added to the grid and at which locations they can be added.
4. Currently both the transmission and distribution grid are designed to transport the centralized produced natural gas. With an integration of more hydrogen producers that inject at other locations in the grid it needs to be determined to what degree the design and operation of the gas grid can adopt more producers.
5. Currently, hydrogen is predominantly produced with fossil fuels as energy input. The hydrogen production capacity reaches approximately a sixth of the total demand needed to replace the distribution grid connection (van den Noort et al., 2017). When green hydrogen should be produced production capacity shortages are higher. Green hydrogen is dependent on the surplus of renewable electricity, which is currently nihil in the Netherlands and not likely to increase rapidly.
6. The underground hydrogen storage capacity in the Netherlands is currently a twentieth of what is needed. Smaller-scale storage facilities are currently too cost-intensive in CAPEX and OPEX.

### **Coordination – Technical operational**

1. The operational activities of the natural gas extraction and storage are monitored and supervised by the SodM. A supervisory body needs to exist that monitors and controls the production of hydrogen.
2. The same applies to the storage activities. The SodM might be a suitable candidate to perform these activities.
3. The technical control mechanism, routines, emergency procedures, and preventive maintenance activities are currently compatible with specific gas standards of natural gas. These mechanisms and activities need to be tested for the use of hydrogen and hence be adjusted where necessary.

### **Access – Economic-institutional**

1. The natural gas and electricity provision are currently regulated from a European and national level. For hydrogen no laws and regulations exist on the same level as for electricity and natural gas. It needs to be investigated where the formal laws and regulations are applicable to hydrogen gas and where not. New laws and regulations need to be formulated both on the European as national level where the current laws and regulations are not applicable.
2. It needs to be determined whether a market for retail supply will be introduced. Important is how the market will function, especially according to the wholesale market.

### **Responsibilities – Economic-institutional**

1. Currently no specific Dutch Hydrogen Act is active. Specific hydrogen laws and regulations need to be adopted before a hydrogen infrastructure can function like the natural gas infrastructure or electricity infrastructure. An extensive hydrogen infrastructure is hence not possible yet.
2. The access regulation on the extraction of natural gas is currently organized through the SodM by a permitting procedure. The regulations on the permitting process is currently stated in the Mining Act. With the different nature of the production of hydrogen, new regulations and permitting procedures need to be formulated. Laws and regulations need to state which requirements are applicable to the permitting process and need to state which supervisory body monitors and enforces these regulations.
3. A transition to a hydrogen infrastructure requires large upfront investments by private and public actors. In realizing a hydrogen infrastructure, it is hence important to include these investment costs in the tariff and cost structures of hydrogen. Private actors will not invest when it cannot be guaranteed that their investment will be earned back.
4. Hydrogen properties differ significantly from natural gas. These properties require new industry standards to be formulated. Standards about the gas qualities, operational pressures, asset characteristics, and temperatures need to be standardized on a European level.
5. The ACM needs to adopt hydrogen codes that are applicable to the provision of hydrogen to a variety of customers.

### **Coordination – Economic-institutional**

1. The production and storage capacity of hydrogen are currently insufficient to replace the demand of natural gas related to the distribution grid connections. The government must introduce proper incentives to stimulate investments in production and storage capacity.
2. The ACM needs to monitor and control the market access in a hydrogen infrastructure just as with natural gas and electricity. This means that the ACM needs to approve hydrogen suppliers and monitor and control the functioning of the market.