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"The feasibility of transforming the Dutch main- and regional natural gas pipeline infrastructure into a Hydrogen network".

M. Sc Thesis

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The Abstract,

The research concerns the extent to which the current regional- and main natural gas pipeline network is suitable for the distribution of hydrogen gas. The technical feasibility and economic feasibility of the transformation to hydrogen were determined within the research. The technical feasibility mainly relates to the materials that make up the pipeline network and the outcomes to which minimum technical requirements hydrogen distribution utilizing pipelines must meet. The economic feasibility is determined based on the investments that must be made to make the network suitable for hydrogen gas. Another factor for economic feasibility is the extent to which hydrogen can contribute in the short term to a sustainable energy system in the Netherlands. This research has shown that the current natural gas network meets the minimum technical requirements that apply to hydrogen distribution utilizing pipelines. Also, the research results have shown that the materials within the pipeline network do not undergo significant degradation when exposed to hydrogen gas under pressure for a long time under real life similar conditions. The economic feasibility of the investments is realistic, but hydrogen must then meet the condition that it is economically viable. This can only be achieved if green electricity exists in surplus, and thus, a profitable green hydrogen market can be created that functions like the liberalized natural gas market. Profitable green hydrogen is not expected in the short term, which leads to the conclusion that the transformation of the natural gas network to a hydrogen network is currently not economically feasible.

Keywords: Natural Gas Network, Hydrogen, Sustainable Energy System, Netherlands, Feasibility

Table of Contents

List of Tables

List of Figures

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List of Abbreviations

CO2	**Carbon dioxide**
Co	**Carbon monoxide**
PSA	**Pressure Safety Awareness**
EU	**European Union**
M3	**Cubic meters**
NAM	**Nederlandse Aardgas Maatschappij**
EBN	**Energie Beheer Nederland**
GTS	**Gasunie Transport Service**
HTL	**High pressure Transport Network**
RTL	**Region Transport Network**
PE	**Polyethylene**
MQR	**Regulation on quality aspects of grid management for electricity and gas**
ISO	**International Organization for Standardization**
ACM	**Authority Consumer and Market**
H2	**Hydrogen**
CCS	**Carbon Capture Storage**
SMR	**Steam Methane Reforming**
CH4	**Methane**
O2	**Oxygen**
IEA	**International Energy Agency**
WEQ	**Housing equivalent**
MS	**Medium voltage**
HT	**High temperature**
MJ	**MegaJoule**
MDPE	**Medium-Density Polyethylene**
HDPE	**High-Density Polyethylene**
PVC	**Polyvinyl chloride**
POM	**PolyMethylene**
NBR	**Acrylonitrile Butadiene Rubber**
SBR	**Styrene butadiene rubber**
MWh	**MegaWatt Hour**
AE	**Alkalyne Elektrolyse**
PEM	**Proton Exchange Membrane**
SOE	**Solid Oxide Elextrolyse**

Definitions

Cathodic	*Cathodic protection is a method of corrosion control and is based on the principle of potential reduction of the object to be protected.*
Wobbe Index	*The Wobbe index is an important characteristic of fuel gases. It is a measure of the interchange ability of different gases on a particular burner.*
Pressure drop	*reducing pressure in a pipe due to distance, friction, viscosity, turbulence and the shape of the pipe*
Permeation	*penetration of substances into cells*
Embrittlement	*Embrittlement is a significant decrease in the ductility of a material, causing the material to become brittle.*
Viscosity	*is a physical material property of a liquid or a gas. It is the property of a fluid that indicates the degree to which it resists deformation by shear stress.*
Odorization	*adding a fragrance to an odorless gas*

Chapter 1. Introduction

1.1 Background

In 2016, the Netherlands signed the United Nations Climate agreement in Paris, With an initial goal: "Limit global warming to well below 2 degrees Celsius". This agreement takes effect in the year 2020. achieve its goal; the EU member states agreed that the EU should emit at least 40% less CO2 by 2030 (Ministery of Economic Affairs Et Al, 2019). The Netherlands has determined the goal of reducing 48% CO2 emissions in 2030 compared to 1990 and within 2050 95% CO2 compared to 2040. To achieve these goals, the Government of the Netherlands, companies, and Civil Society organizations have signed a Climate agreement. All measures that the Government will take are elaborated in the Dutch climate agreement called "Klimaatplan" legal boundaries enforce this agreement due to the Dutch law "Klimaatwet." The first period of this law will start in the year 2020 until 2030. After 2030 the law will be assessed and adjust within ten years (Ministery of Economic Affairs Et Al, 2019).

Energy wise the Netherlands is a natural gas country since the discovery in 1959 of the Groningen natural gas field in Slochteren. With this discovery, the Netherlands owned the largest natural gas field in Europe. Partly due to this discovery and the energy crisis of 1973 in which the Netherlands discovered that it was very dependent on foreign oil, the importance changed, and energy from the Netherlands in natural gas became more critical (Ben Riemersma Et Al, 2019). Natural gas was seen in the 1970s as a relatively clean fuel for industry, electricity production, and domestic heating. Due to the discovery of the natural gas field in Slochteren, the Netherlands has become the largest natural gas producer in the European Union (D. Hulshof Et Al, 2016). The Netherlands is also a key player in the purchase and sale of natural gas. The Netherlands is therefore seen as a natural gas roundabout within Europe. The Netherlands owes this to its strategic position and the highly advanced infrastructure developed for the production, transport, storage, and transit of natural gas (Ministery of Economic Affairs, 2017).

After 60 years, the Netherlands no longer wants to be dependent on natural gas for its national energy supply. That is why the national government agreed on the climate agreement and set goals for a fossil-free energy system in 2050 (Ministery of Economic Affairs and Climate Policy, 2019). As a result of this, the Netherlands has set a road map to energy savings on a national scale and a step-by-step transition towards sustainable energy. This transition will take place in the next 30 years within the Netherlands. Nobody knows what the energy mix will look like in the future. However, developments and studies have been carried out that provide a trustful prediction of what a possible energy mix may look like in the Netherlands (Delft, 2018). These studies have shown a significant role for different forms of energy as Off-shore wind energy and solar energy (Ad van Wijk Et Al, 2018).

This is because the Netherlands has enough space in the North Sea to produce offshore wind on a large scale. This possibilities offers opportunities to make the energy system in the Netherlands more sustainable. Nevertheless, these sources of energy also have a significant disadvantage. The disadvantage is the fact that these forms of energy depend on the weather (L. Lakatos Et Al, 2011). There will be times when there is not enough solar and wind energy to provide the Netherlands with the required electricity. An excellent national energy system must be reliable and stable, and this cannot be guaranteed if the sources of energy depend on the weather (P. Mancarella Et AL, 2016). To guarantee stability and reliability, Netherland needs a buffer in which energy is stored to be used when a national shortage threatens. Research has shown that hydrogen can be a solution to this (Ad van wijk et al, 2018). Hydrogen is used as a storage medium to store clean energy on a large scale by converting electricity into hydrogen gas. Suppose green electricity can be produced in surplus in the future (Delft, 2018). In that case, it is an option to use this residual flow to create a buffer that can make the sustainable energy system in the Netherlands reliable and stable. Studies show that energy from molecules is indispensable for energy supply. Also, electricity is not the most suitable alternative everywhere. Besides, the electricity grid can never become so large that every sector can be supplied with electricity at any time of the day (Gasunie Tennet Et Al, 2020).

Gasunie expects that approximately 30-50 percent of the energy supply will consist of molecules in 2050. These are mainly sustainable gases that are used to achieve the high temperatures required within the industrial sector, furthermore, as fuel for other sectors that cannot all obtain their energy from electricity. However, also as a buffer medium for times when less energy is available from wind turbines and solar parks. The Netherlands must, therefore, prepare itself for the fact that sufficient infrastructure is available to transport and store all those molecules. In this research, the sustainable gas, in this case, is hydrogen. Due to the phasing out of natural gas within the Netherlands, a high-quality gas distribution network will eventually become available to which 97% of Dutch households are connected. Besides, the Netherlands also has 60 years of experience in the field of gas distribution. This gives rise to whether the natural gas network can contribute to making the energy system in the Netherlands more sustainable by 2050, following the energy agreement whereby the network facilitates the distribution of hydrogen molecules instead of natural gas. This research investigates whether the Dutch main- and regional natural gas pipeline network is technical and economically feasible for the distribution of hydrogen gas instead of natural gas with the central question:

"Is it technically and economically feasible to use the current Dutch main- and regional natural gas pipeline network for the transportation of hydrogen gas? If yes, which adjustments must be made and to contribute to a carbon-free energy system by 2050 in the Netherlands?"

This central question is divided into four different sub-questions:

- *What are the characteristics of hydrogen gas and which technical requirements must an hydrogen gas distribution network due gas pipelines meet?*
- *How is the Dutch Natural gas main- and regional pipeline network working and which materials are used within the gas piping network?*
- *To what extent is the material within the existing main- and regional natural gas pipeline network in the Netherlands technical suitable for the transport of hydrogen gas?*
- *Which technical adjustments must be made to make the natural gas network in the Netherlands technically suitable for hydrogen and are these adjustments economically feasible?*

1.2. Methods

The basis for this research is a literature study using qualitative data. To ensure validation, triangulation is used in which different forms of qualitative data and sources have been applied, such as in-depth interviews with experts, scientific reports, and data from government agencies. Within the research, data analysis software was used; in this case, atlas. The interviews and reports are clearly analyzed by combining different sources and data, and reliability and validity are guaranteed (Baarda, 2014). For the study, five depth interviews were conducted with experts in gas distribution from Gasunie, GasTerra, KIWA, and the University of Groningen. The research is divided into different parts in which technical and organizational aspects are examined to provide a clear picture and answer to the main question. The research aims to map the extent to which the main and regional natural gas network is suitable for hydrogen gas distribution through pipelines.

This involves assessing the technical feasibility and economic feasibility. The technical feasibility defined within this study as the extent to which the material from which the pipelines are made do not undergo degradation when exposed to long-term hydrogen gas under pressure. Aspects are linked to this that gives an indication of the quality of the materials used for the network's pipelines. The basis of the research are the characteristic differences between hydrogen gas and natural gas. The characteristic features of hydrogen say something about the safety profile of hydrogen. The safety profile of hydrogen is determined on the basis of the explosion- and fire hazard of the flammable gas. The characteristic features and the safety profile of hydrogen is uses as the input that for the risk analysis. From this risk analysis, technical conditions have emerged that hydrogen distribution utilizing pipelines must at least meet.

To answer the main question, this study investigated how the main- and regional existing natural gas network works technically and organisationally. Within the technical aspect, the main focus is on the materials of the pipelines. To assess the quality of pipelines an analysis is done on which aspects determine the quality of the gas pipeline materials. Further, in the research, it was determined to what extent these materials are resistant to hydrogen on the following aspects: material fatigue, permeation, hydrogen embrittlement, leakage risks, and erosion of pipes. The technical analysis has revealed which adjustments need to be made to the network and which investments need to be done. This is important in order to test the economic feasibility based on the adjustments within the network. Finally, the economic feasibility is linked to the investment and the feasibility of hydrogen and whether this energy carrier can make a contribution in the short term within an sustainable energy system for the Netherlands. a detailed schematic of the used research framework can be found in appendix 4.

1.3. Reading guide Chapter

1. introduction of the background, problem statement, research objective, main research questions, sub research questions and the used research design & methodology.

2. General information about the history, technical information, current status of the natural gas distribution network in the Netherland and hydrogen technology.

3. Comparison of characteristic properties of hydrogen gas versus natural gas, with an risk analysis of hydrogen and the minimal technical requirements for safe hydrogen distribution due an network of pipelines.

4. Analysing the Natural gas main- and regional pipeline network on technical requirements and materials for the distribution of natural gas within the Netherlands.

5. Analysis to which extent the materials of the pipelines within the regional- and main natural gas network in the Netherlands are technical suitable for the distribution of hydrogen and if this network meets the minimal requirements for safe hydrogen distribution. Including the assessment of the economically feasibility of this transformation.

6. Conclusion, recommendations and discussion, explaining the finding of the research of the technical and economic feasibility for transforming the natural gas network into and hydrogen network.

Chapter 2. Document review & Literature study

2.1 General information Dutch natural gas industry & network

The Dutch natural gas network consists of an infrastructure of 136,000 kilometres of pipelines. In 2015, domestic gas consumption was approximately 45 billion M3, with 10.5 billion M3 consumed by households. The average costs of 1/M3 natural gas for domestic use within the Netherlands is €0,77 after taxes. The Netherlands' industry was responsible for the consumption of 10 billion M3 natural gas and the energy sector for 13 billion. With this domestic consumption, a total amount of 4.5 billion is captivated only in tax revenue for the Dutch state. In total, there are 250 different gas fields where natural gas is extracted, the largest gas field on both land and offshore is the Groningen gas field in Slochteren. Total natural gas revenues for the Netherlands in 2015 were approximately 9.1 billion euros. The natural gas and oil market in the Netherlands is a significant employer with approximately 16,500 jobs in the sector (Nederland Netbeheer, 2019).

The Netherlands is the largest natural gas producer in Europe, and it also plays a leading role in the purchase and sale of natural gas. The Netherlands is also known as the gas roundabout of Europe. This is partly due to the high-quality natural gas infrastructure in production, transport, storage, and transit of natural gas. In addition to the fact that the Netherlands produces itself, foreign natural gas also comes in from countries such as Norway and Russia, which in 2016 was approximately 35.2 billion m3 (Gasunie, 2020). The natural gas that is imported has a different calorific value than the natural gas produced in the Netherlands. For this reason, there are two different networks in the Netherlands: the High-caloric network and the Low-caloric network.

The largest producer of natural gas in the Netherlands is the Nederlandse Aardolie Maatschappij (NAM), in which Shell and ExxonMobil work together on the extraction of natural gas and oil. Each year, NAM produces approximately 20 billion M3 natural gas and is responsible for 75% of Dutch natural gas production, the majority of which from the Groningen gas field (Ben Riemersma Et Al, 2019). Because the Natural gas production and the discovery of the Groningen gas field in Slochteren were and are of great importance for Dutch prosperity, there was a collaboration between the state of Shell and ExxonMobil on the extraction, transport, and sale of natural gas, this agreement was concluded in 1962 established in the form of the gas building, which consists of the NAM, Maatschap Groningen, GasTerra and EBN. Maatschap Groningen is responsible for the exploitation of the Groningen field, and Gasunie was also established (Ben Riemersma Et Al, 2019).

The trade organization that deals with the purchase and sale of natural gas are GasTerra, Gasterra originated from Gas Union. At the beginning of the 1960s, Gasunie was responsible for the transport and trade of natural gas, this changed in 2005 when the transport company became wholly owned by the state. The trading company became Gasterra with the Dutch state owning 50% and Shell and Exxon mobile, both 25%. Within the gas building, EBN is responsible for looking after the Dutch state. EBN is also wholly owned by the Dutch state (Gasunie, 2020). Gasunie is responsible for the main transmission network for natural gas in the Netherlands and its storage. The main transmission network is responsible for transmitting the national gas fields to the regional network operators and the international gas market. The main natural gas transmission network consists of 2 separately network of pipelines for the transport of low calorific gas and high calorific gas. The low calorific gas is mainly extracted from the Groningen gas field in Slochteren, which is also the largest natural gas field in Europe. This main natural gas transmission network is managed by GasUnie Distribution Service (GTS) (GTS, 2017).

In the Netherlands, there are 25 regional natural gas network operators responsible for transporting natural gas from the gas stations with local low pressure gas pipelines to the domestic end-user as households and the local industry. Because different network operators work together, a distinction can also be made between 13 natural gas network operators. The four largest regional managers together have a joint share of 85% of the market (Ben Riemersma Et Al, 2019). The regional network operators together have a turnover of approximately 800 million euros. This amount is based on 10% of the gas bill that goes to the managers. The regional network operators facilitate the transmission of natural gas to the end-user. The actual end-user buys the gas from a natural gas supplier in the Netherlands. So the natural gas network operator facilitates the transmission and the network, whereby the natural gas supplier supplies the actual natural gas purchased from the umbrella natural gas company GasTerra. In this way, the natural gas chain is organized at the organizational level in the Netherlands (Erik Polman et al, 2018).

2.3.General information Hydrogen energy

Hydrogen is the smallest and lightest molecule we have discovered to date on Earth. The chemical element of hydrogen is H with atomic number 1. Hydrogen is the lightest and most abundant element in the universe. 75% of the matter discovered so far contains hydrogen. Pure hydrogen is rare on earth 0.000006% of the total atmosphere is hydrogen (Aue, 2018). Hydrogen can form a flammable mixture combined with air, which can be ignited through a spark or heat of approximately 500 degrees Celsius. Hydrogen is often seen as a source of energy such as fossil fuels such as natural gas, oil, or sustainable sources such as wind, sun, and hydropower, but this is not correct. Hydrogen is an energy carrier, fuel or transport medium. We must produce hydrogen because it rarely occurs in pure form. Hydrogen is quantified in different types depending on the production method. Usually, a distinction is made between Gray, Blue, and green hydrogen (Christos M. Kalamaras et al, 2013). a detailed explanation of the different production methods can be found in appendix 3.

Grey hydrogen,

Hydrogen is produced from fossil fuels, the most commonly used sources for this are natural gas or coal. This form also releases CO2 and is not a form of sustainably produced hydrogen. From the perspective of the energy agreement, this is not an option for making the energy system more sustainable in the Netherlands (Christos M. Kalamaras et al, 2013).

Blue hydrogen,

Hydrogen is still produced here through fossil fuels, but in this form, the CO2 released during production is captured and stored or used for other chemical processes. This can be done above ground or underground. This is also called Carbon Capture Storage (CCS). The production process is still not completely sustainable, but capturing the CO2 does not contribute to the greenhouse effect. During the transition phase, this form of production can help create a hydrogen market within the Netherlands (Machiel Mulder Et Al, 2019).

Green hydrogen,

Hydrogen is produced in this way by means of sustainable energy, usually from wind, sun, or hydropower. Electricity from wind, sun, or water is converted into hydrogen by electrolysis. This is also the form of hydrogen that can ultimately be used in the sustainable transition within the Netherlands' energy system. Because hydrogen is now a sustainably generated gas that can provide energy. (F. Tabki Et Al, 2008).

2.2.1 Hydrogen Production Processes

Because hydrogen does not naturally occur in a pure form, it must be produced, and there are various methods. The most common method is Steam Methane Reforming (SMR). Steam (H20) reacts under high temperature with natural gas (CH4). This reaction releases hydrogen (H2) and carbon monoxide (CO) or carbon dioxide (CO2). Another common way is to produce hydrogen by electrolysis in which water (H20) is split into hydrogen (H2) and oxygen (O2) (Machiel Mulder Et Al, 2019). Both production methods use different forms of energy. SMR mainly uses natural gas, but this could also be in the form of biomethane. What is produced from residual organic material. Electrolysis uses energy in the form of electricity to produce hydrogen. Green hydrogen is made from electricity from sustainable sources, within Europe there is a tracking and tracing system where sustainably generated electricity has a certificate, this is done otherwise it is very difficult to find out whether certain electricity is sustainable, This is guaranteed by means of this system (IRENA, 2018).

Within Europe, there is an Emmissions Trading Scheme, the starting point of this system is that there is paid for the CO2 emitted during the production of electricity, which is expressed in price per ton of CO2 (Bloomberg, 2010-2018). Because this amount is fixed, it makes no difference how electricity is produced, for the production of hydrogen this can cause problems for the production of sustainable green hydrogen.

Mehods	Advantages	Disadvantages
Steam reforming CH4	- 65-75% efficiency - Economical least expensive - Established infrastructure	- Nonrenewable resource - Produces CO2 emission
Gassification	- Inexpensive resources	- Produces CO2 Emmision - Carbon Sequestration would raise costs - 45% efficiency
Electrolysis of water with wind energy	- No emission - 65% efficiency	- Expensive

Table 1: Hydrogen Production Methods **(Chamousis, 2016)**

Specification of Hydrogen production			
Name	***Production technique***	***Type of energy used***	***CO2 Treatment***
SMR-Grey	Steam methane reforming	Natural gas	Emitted
SMR-Blue	Steam Methane Reforming	Natural gas	CCS
SMR-Green	Steam Methane Reforming	Green Gas	No emmission
Electrolysis- Grey	Electrolysis	Electricity	Out of scope electolyser
Electorlysis-Green	Electrolysis	Green electricity	No CO2 emmission
Electrolysis-Orange	Electrolysis	Green electricity from Holland	No CO2 emmission

Table 2: Specification of Hydrogen Production **(Christos M. Kalamaras et al, 2013)**

2.2.2 Hydrogen energy system

The question of why hydrogen is seen as a potential energy carrier and specifically for the Netherlands relates to the energy issue that the whole world is dealing with. We can produce green electricity on a large scale, the price of this green electricity is expected to plummet and thus become very affordable. This seems to solve the green energy demand. But the problem that arises here is that this green power is not continuously available, therefore the security and reliability cannot be guaranteed. The power that has been generated must be used immediately or it must be stored in an energy carrier (Gasunie Tennet Et Al, 2020). This is the moment when hydrogen enters. Hydrogen can be a form in which the green energy can be “stored” for use at a later time. The hydrogen thus becomes a gaseous fuel like natural gas. The Netherlands has several crucial success factors in its possession that represent a good potential for hydrogen: Distribution infrastructure, Production capacity, and demand. Because of this, hydrogen is seen as a key player in the energy transition of the Netherlands. A practical example is Japan where they have almost no natural sources of energy. There they are busy importing green hydrogen from Australia to make their energy supply more sustainable (Aue, 2018). Within the Netherlands, it would be mainly seasonal storage to produce energy for heating homes in winter. There are many positive sides to hydrogen, but hydrogen also has disadvantages. The biggest disadvantage is that the efficiency to make green hydrogen is still 60-70% and therefore not yet profitable. Hydrogen has a large energy content per kg mass, this amounts to 140MJ / KG hydrogen, with natural gas this is approximately 42 MJ / KG. Besides, the energy content per volume is much lower, the consequence of this for the transport of hydrogen is that it must be stored under high pressure to transport enough energy (Ad van wijk et al, 2018).

2.2.3 Hydrogen Fuel of the future

Hydrogen is already widely used in the world in the automobile, aviation, and chemical industries. In recent years, many studies have been published about hydrogen and the possibilities/developments of this technology. This is not just researched, because the world is also seriously examining the possibilities of how hydrogen can contribute to a clean, secure and affordable energy system, this is evident from the report "The future of Hydrogen" published by the International Energy Agency (IEA) for the G20 2019 in Japan (IEA, 2019). This report focuses on the global potential of hydrogen and how it can contribute to a clean energy system. In addition to worldwide, Europe is looking specifically at how hydrogen can be implemented in energy systems, Europe has stated that it wants to become a frontrunner in hydrogen. That is why the European Hydrogen and Fuel Cell Association, also known as "Hydrogen Europe," has been established within Europe, involving 160 companies, 78 research institutes, and 21 National Associations. To promote hydrogen innovation and facilitate its laws and regulations as much as possible (Hydrogen Europe, 2019). On the subject of hydrogen energy, the Netherlands has set goals for itself within the energy agreement and translated this into a multi-year programmatic approach for hydrogen (MPAW) that consists of five components that are interconnected that the Netherlands has started to deploy on hydrogen is partly due to the phasing out of the natural gas use. (Ad van Wijk Et Al, 2018). There are also several large-scale hydrogen initiatives in the Netherlands, such as NortH2, Hystock and the Hydrogen Backbone.

Chapter 3. Hydrogen gas versus Natural gas

It is essential to map out the risks associated with hydrogen distribution through pipelines. The reason for this is that hydrogen, just like natural gas, entails a fire- and explosion hazard. That is why the safety aspect and risk perception are of great importance for honest hydrogen distribution through pipelines. An additional factor is that hydrogen is only socially acceptable if the safety standards and transport applications are equivalent to those of natural gas (Ad van wijk et al, 2018)This chapter examines which conditions the safe distribution of hydrogen utilizing pipelines must meet. First, the characteristic properties of hydrogen and natural gas were mapped out and compared. These properties were explicitly selected for aspects that provide a clear picture of the explosion and fire hazard of an energy-carrying gas and the associated safety risks. The comparison between natural gas and hydrogen provides input for the risk analysis of hydrogen and the minimum conditions that must be met by integer hydrogen distribution through pipelines.

3.1. Characteristics natural gas

The natural gas quality to be supplied has certain technical characteristics this is captured in the “Gas Quality Regulation” Act and is described in the Gas Quality Code (Gaswet, 2000). For suppliers, delivery conditions have been determined within a quality frame that they must adhere to. The national grid operator has the task of monitoring this utilizing random audits. Within this law, a distinction is made between L-Gas and H-Gas (Gaswet, 2000). The main difference between L and H gas is the thermal power shown in the Wobbe index, which represents the calorific value of a gas in Mega Joules per M3. the natural gas is transported at a temperature of 15 degrees Celsius at a pressure of approximately 1.013 bar in gaseous state. H gas mainly comes from smaller gas fields in the Netherlands and the North Sea. Since 2014, all H-gas that meets national standards has been authorized with the maximum Wobbe index of 55.7MJ / M3. The vast majority of the Netherlands is connected to the Groningen gas, also known as L-gas. The big difference between H-gas and L-gas is that the Wobbe index value of L-Gas is lower with a value of 43.46-44.41 MJ / M3. Gases such as natural gas can catch fire by a spark or by heating to the ignition temperature. It is essential to map this entails several consequences concerning safety that are of great importance in the distribution of explosive gases. Table 3 shows the most critical aspects of the safety of the gas and which risks may arise

Characteristics	Unit	Natural gas
Wobbe index	Mj/M2	55.7 (H-Gas) 43.46 (L-Gas)
Molecular weight	U	16
Density related to air		0,55
Diffusion coefficient	Cm2/s	0,16
Explosion energy	MJ/m3	32
Flammability range	Vol%	5 - 15
Ignition range	Vol%	6 - 14
Minimum ignition energy	mJ	0,29
Flame speed	Cm/s	43

Table 3 Characteristics Natural Gas **(Ministery of Economic Affairs, 2017)**

3.2. Characteristics Hydrogen gas

the laws, regulations and policies regarding hydrogen are now mostly based on its use as an industrial gas and as a raw material for chemistry. After all, hydrogen has been used in industry for much longer. As a result, the rules for the use of hydrogen in new applications - such as cars, trains, or the built environment - may be relatively strict, they are not (yet) sufficient, or there are no regulations yet ((Ministery of Economic Affairs, 2017). In a gaseous state, hydrogen is very flammable, and because it is a light gas, it spreads quickly, which has consequences concerning safety. Hydrogen has significant energy content per kg mass. The energy content is approximately 140 MJ / kg hydrogen; for natural gas, this is approximately 42 MJ / kg. On the other hand, the energy content per volume is much lower, so that hydrogen often has to be stored under high pressure to be able to transport sufficient energy. (approx. 11 MJ/NM3 for hydrogen against 36MJ/NM3 for natural gas at atmospheric pressure). Compared to gasoline: liquid hydrogen has an energy content of approximately 8.5MJ/L against 33 MJ/L for gasoline (Chamousis, 2016). In the table 4 are the main properties of hydrogen that say something about the safety and risks that may apply when distributing the gas employing pipelines.

Characteristics	Unit	Hydrogen
Wobbe index	Mj/M2	140
Molecular weight	U	2
Density related to air		0.07
Diffusion coefficient	Cm2/s	0.61
Explosion energy	MJ/m3	9
Flammability range	Vol%	4 - 75
Ignition range	Vol%	18 - 59
Minimum ignition energy	mJ	0.02
Flame speed	Cm/s	346

Table 4 Characteristics Hydrogen gas **(Ministery of Economic Affairs, 2017)**

3.3. Hydrogen VS Natural gas

To gain an overview of the differences between natural gas and hydrogen, an comparison has assessed on the characteristically aspects. This comparison indicate safety and potential risks on behalf of explosion and flammable hazard, for hydrogen distribution due pipelines (M. Melaina Et Al, 2013). This is shown in table 5. This comparison has revealed several aspects that may pose the main risk of the distribution of hydrogen gas through pipelines in the fire and explosion hazards. These aspects form the basis for the risk analysis that has been created within this research

- Hydrogen atoms are three times smaller than natural gas atoms.
- Hydrogen is eight times lighter than natural gas and therefore spreads quickly
- To ignite hydrogen, 13.5x less energy is needed than natural gas.
- The flame speed of hydrogen is considerably higher than that of natural gas.
- Hydrogen forms a flammable mixture with air.

Characteristics	Unit	Hydrogen	Natural gas
Wobbe index	Mj/M2	140	55.7 (H-Gas) 43.46 (L-Gas)
Molecular weight	U	2	16
Density related to air		0.07	0,55
Diffusion coefficient	Cm2/s	0.61	0,16
Explosion energy	MJ/m3	9	32
Flammability range	Vol%	4 - 75	5 - 15
Ignition range	Vol%	18 - 59	6 - 14
Minimum ignition energy	mJ	0.02	0,29
Flame speed	Cm/s	346	43

Table 5 Comparison Hydrogen and Natural gas **(Ministery of Economic Affairs, 2017)**

3.4. Risk analysis Hydrogen

From the comparison of hydrogen with natural gas, aspects have emerged that pose safety risks in the explosion and fire hazards. The risk analysis has been set up based on these aspects. This revealed the following about the risks of hydrogen distribution through pipelines. The most important aspect is that a hydrogen molecule is a factor 3 smaller than natural gas, which increases the risk of leaks within the network (H.Iskov Et Al, 2017). The fact that a hydrogen molecule is small does not increase all safety risks, because it is so small and light it reduces the chance of forming a flammable mix with oxygen. This is because it dissipates quickly in the atmosphere. After all, it is lighter than air, so the density of hydrogen atoms in the air is not great enough for a flammable mixture. Because hydrogen is lighter than air, there can be an increased risk in case of leakage in closed spaces because it spreads so quickly in a closed space and, therefore, an explosion cloud. This is not only a risk with hydrogen but also with natural gas (S.D. Paul Et Al, 2013). The flammability of hydrogen is 13.5 times greater than natural gas. This poses a major risk of explosion and fire, which, combined with the risk of leakage, is crucial for sound hydrogen distribution and forms the basis for the technical conditions for safe hydrogen distribution utilizing of pipelines.

Characteristics	Critical Aspects	Assets
Small molecule	Challenge of leak tightness of the hydrogen network	Reduce chance of accumulation to a flammable mixture
Lighter than air	risk of accumulation in closed areas that are not ventilated	High ascent speed making fast dilution in air occurs in open spaces
Flammable mixture with air with a wide range of concentration	point of attention in closed and bad ventilated areas	lower bound not fast achieved by inclination to rapid dilution in air
Low ignition energy	Critical aspect also for other flammable gasses and vapors	
High burning rate	High flame temperature, and risk of flashback witha limited one outflow rate of hydrogen.	Limited flame front what the risk of fire spread limited
colorless flame	By lower radiant heat and not or are less visible from a hydrogen flame is the chance to not notice the hydrogen flame	hydrogen flame produces less radiant heat increasing the chances of fire spread less is.
Hydrogen is odorless	Odorization and / or detection sensors required	

Table 6: Risk analysis Hydrogen distribution **(M. Melaina Et Al, 2013)**

The most important safety aspect in the transmission of hydrogen through the natural gas network in the Netherlands is to keep the pipes gastight. This is more challenging than with natural gas because hydrogen is a 3 times smaller molecule than methane. The safety aspect of the natural gas network is safeguarded by the standardization of bodies such as ISO and regulations and a legal framework within the Netherlands in the form of the Gas Act, and laws on energy distribution that are determined by the national government. (ACM, 2019). Hydrogen has different properties than natural gas, so new guidelines and a legal framework for hydrogen distribution must be introduced. Research has shown that Europe and the Netherlands are working on this, and it is expected that in 2020 Europe will propose a legal framework around hydrogen distribution. The use of hydrogen within the Netherlands' energy system must become at least as safe as the use of natural gas (Gaswet, 2000). From a report by TNO in 2020, there were a total of 45 leaks in 2018, which is relatively little when looking at the size of the network. Nevertheless, there are situations imaginable with hydrogen, where small losses can form into a flammable mixture with air, which is, therefore, a severe risk. This type of situation is small in homes, but specific research is needed into the chance of leaks and the consequences of this because leaks release approximately one and a half to three times as much hydrogen under the same pressure as natural gas. (Marcel weeda Et Al, 2020). This is due to the lower density and Viscosity of hydrogen compared to natural gas. The lower ignition energy of hydrogen and the larger concentration range in which hydrogen in air forms a flammable mixture is a risk. However, with small leaks, the risk is considered negligible (Regionale Netbeheerders gas, 2003). to rule this out, studies are yet to be conducted into these risks. If excavation damage is involved in activities involving a significant leak, the risk increases compared to natural gas, the flame is also poorly visible, which carries a higher risk. However, it is the case that hydrogen produces less heat

3.5.Chapter Conclusion

Hydrogen gas has several characteristic features compared to natural gas. A hydrogen molecule is a factor 3 smaller than natural gas. One of the technical conditions for a hydrogen pipeline is that more attention must be paid to making the network gas-tight. Besides, hydrogen is lighter than natural gas and spreads quickly in spaces. For this reason, a higher safety risk can arise in closed spaces that are poorly ventilated. A technical condition for a hydrogen network is that hydrogen detectors must be used in closed spaces. Hydrogen is odorless. For this reason, Ordorisation must be applied within a hydrogen network, which is also the case with natural gas. This means that an odorant is added to the hydrogen gas so that in the event of a leak, the gas is smelled and noticed earlier. The lower ignition energy of hydrogen and the larger concentration range in which hydrogen in the air forms a flammable mixture is a risk. This is not only a critical aspect of hydrogen, but it applies to all flammable gases. For hydrogen, higher technical requirements must be applied that determine safety than natural gas, because the risk profile of hydrogen is higher than that of natural gas. A technical precondition for this is that the influence of hydrogen on various material properties must also be examined, particularly the pipelines used within the existing main and regional natural gas network.

Chapter 4. Dutch natural gas pipeline network

To answer the main question of whether the existing regional and main natural gas pipeline network is suitable and resistant for hydrogen distribution, it is necessary to map out how the network works and what materials it consists of. In this chapter, aspects are mentioned about how the network operates, the construction material and potential risks that may arise from hydrogen gas distribution concerning the elements that make up the existing natural gas network. Besides, the transport capacity is analyzed and aspects of the field of gas compression and reduction, and finally, legislation and regulations that apply to natural gas distribution.

4.1. Operation- and construction integrity pipeline network

Because flammable and explosive gases are distributed throughout the network, the network's integrity is of paramount importance (NATURALY, 2010). The social interest is safeguarded by legislation and regulations regarding natural gas distribution laid down by the Dutch government within a legal framework. This is to guarantee the security level of the network (Gaswet, 2000). GTS regularly carries out preventive maintenance to ensure that the underground pipes are in good condition. Aboveground pipelines are coated and subjected to visual inspections. The underground pipes of the network are coated and catholically protected against corrosion (Arcelor Mittal, 2016). The integrity of the transport system is ensured utilizing an on-going inspection program (Gasunie hoofdgasnet, 2014). The regional network operators should report to the government every two years on the safety and integrity of the network; this ensures that the natural gas network remains at a high-quality standard.

4.1.1. Operation of the regional- and main gas network

The Dutch natural gas pipeline network consists of the main transport network (HTL) and regional transport network (RTL). The amount makes the distinction between these networks of pressure on the natural gas pipelines. The regional transport pipelines are the pipelines with natural gas under a pressure of 40 bar, the natural gas pipelines under a pressure of more than 40 bar fall under the main transport network (Gasunie, 2020). The HTL network is a managed gas transport service (GTS) owned by the Dutch government as are most RTL networks. The regional network operators are responsible for the low-pressure pipelines that transport the natural gas from the gas-receiving stations linked to the RTL to the end user, such as homes and regional companies. The entire Dutch natural gas pipeline network has been designed based on national and European standards that apply to fire and explosion hazardous gas (Gaswet, 2000). In the Netherlands, the main natural gas network is designed separately for H-gas and G-gas. It is known that the network consists of two gas pipelines for the distribution of High calorific gas and Low calorific gas. The reason for this is the discovery of the natural gas field in Slochteren Groningen. This discovery has caused the Netherlands' energy system to change drastically and became more dependent on natural gas. Groningen gas has a different composition than natural gas from other parts of the world. When this became known in 1970, the Netherlands chose to build a separate network for this H-gas to which industrial gas users, power plants and international exports are linked (Ben Riemersma Et Al, 2019). Figure 1 shows an overview of the pipeline infrastructure within the Netherlands.

Figure 1 Schematic Main Gas Network Netherlands ***(Gasunie, 2020)***

The HTL consists of several networks with which gases of different compositions are transported side by side. The HTL is linked to the RTL, networks of other Transmission System Operators (national borders), producers, storage facilities, (large) domestic end-users, and a limited number of links with networks of regional network operators (Gasunie T. , 2020)Power plants, (large) industries, and the networks of the regional network operators are linked via a gas receiving station (GOS). The RTL is fed from the HTL. At a few points, the RTL is fed with gas from gas extraction, syngas, and biogas. On the exit side, the RTL is connected utilizing gas receiving stations to the low-pressure networks of regional network operators and (small) industries and power stations (KIWA, 2018). Through this network, the natural gas reaches the residential users and small regional companies. Figure 1 shows a schematic overview of how the high-pressure gas pipeline transport network in the Netherlands is structured.

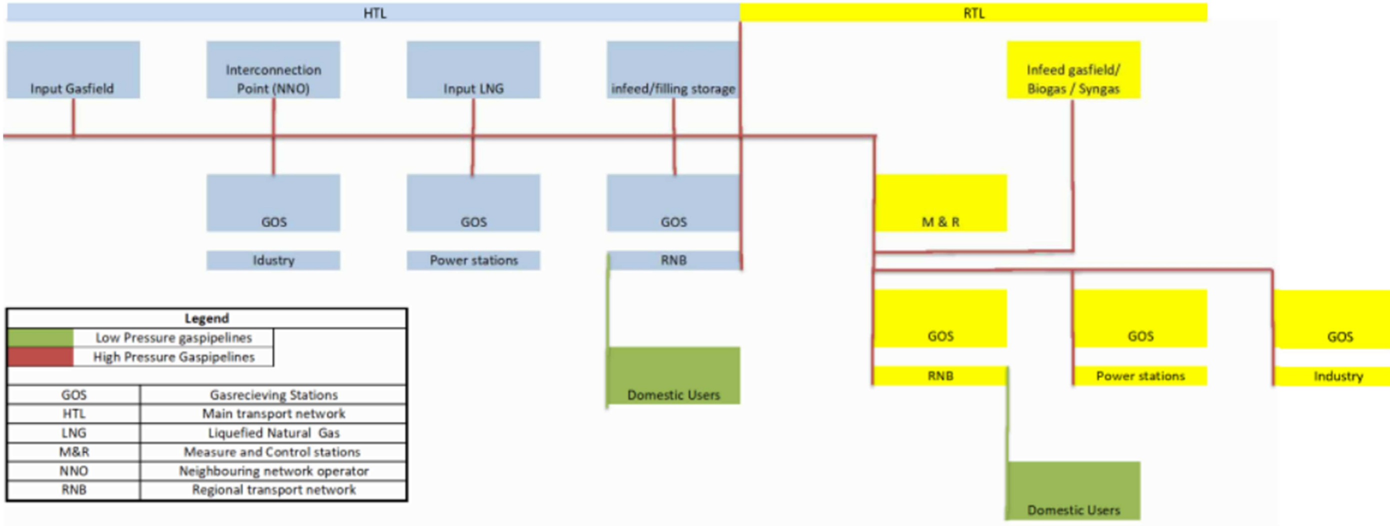

Figure 2 Schematic overview HTL & RTL Netherlands **(Network Configuration GTS, 2014)**

4.1.2. Technical Characteristics of installations and components

The entire infrastructure consists of many installations that form a complex and sound gas network within the Netherlands. The most important part of the network is the pipelines because they form the natural gas distribution medium. Nevertheless, in addition to the pipelines, several installations are essential for a properly functioning natural gas distribution system. The main installations are shown below in Table 7.

Natural gas transportsystem stations and installations	
HTL	*RTL*
Compressor stations	Measure and control stations
Mixing stations	Valve locations
Reducing stations	Reducing stations
Gas receiving stations	Gas receiving stations
Interconnection points	
Valve locations	

Table 7: Natural gas transport system stations and installations **(GTS, 2017)**

4.1.2.1. Compressor station

A compressor station is part of the gas transport system. This part is necessary to maintain pressure when transporting gas over long distances. This is done through a compressor. When natural gas is transported through the pipeline, the pressure decreases. Therefore, to allow the additional throughput of gas under proper pressure, the pressure must be increased at an interval of 65-160 kilometres (F. Tabki Et Al, 2008). The distance at which a compressor station should be placed has to do with various factors such as height difference and how many gas sources are connected. A compressor station provides pressure and compression to move the gas from the start to the end station. The station's size depends on the thickness of the connected pipelines and the amount of natural gas that is transported. The most common drives for compressor stations are; Gas turbine, Electric motor, and piston engine. A gas turbine uses gas supplied from the pipelines to drive a centrifuging compressor. An electric motor drives the centrifuging compressor utilizing an electric motor, an advantage of this is that this system does not need to use the incoming gas. Therefore no greenhouse gases are generated on the location (S.D. Paul Et Al, 2013). A piston engine sucks the gas into cylinders. It then pushes it back through the pipeline, an advantage of the piston engine is that it can deliver the amount of natural gas with high accuracy according to user demand. GTS manage 22 compressor stations in the Netherlands (Services, ontwerp uitgangspunten transportsysteem , 2014).

4.1.2.2. Mixing station

The function of a mixing station is to mix natural gas of different compositions so that the natural gas complies with the established delivery quality as set out in the Dutch gas law. Mixing stations have a specific minimum and maximum capacity per installation, depending on the pre-pressure. The maximum capacity is based on differential pressure across the mixing station. The minimum capacity is based on the minimum capacity of the control line at maximum inlet pressure. The actual capacities of a mixing station depend on the actual outlet pressure and the available differential pressure. Mixing stations are controlled on the calorific value of the outgoing gas or the Wobbe index or both. Mixing stations are equipped with so-called quality blocking loops. These are pipe lengths intended as quality assurance to prevent detected deviations in quality so that the natural gas is not injected into the network (Gasunie Et Al, 2018).

4.1.2.3. Gas receiving station

The gas receiving station forms the connection between the HTL and the transmission network of a regional network operator or the gas pipeline of an industry. Their main role is to reduce transport pressure and to measure the amount of natural gas supplied. The gas pressure is reduced in a gas receiving station to approximately 8 bar. Two or more streets are set up within a gas receiving station, one tail being in principle designated as a reserve ((Gasontvangststations, 2018). It is determined for each receiving station whether the control capacity of the station is sufficient to be able to supply the requested quantity of natural gas following the contractual delivery pressure. The available inlet pressure is essential for the control capacity of a station, the minimum network pressure of the RTL is 16 bar, and the HTL is 43.5 bar. GTS manage 1,200 gas receiving stations in the Netherlands (ACM, 2019).

4.1.2.4. Reducing stations

The function of a reducing station is to maintain an absolute pressure on the inlet or outlet side or to maintain a gas flow using pressure reduction of the natural gas. The capacities are based on station-specific technical achievable capacities at a given pressure loss and specified pre-pressure. The capacity per control line depends on the current inlet pressure and the available pressure drop (GTS, 2017).

4.1.3. Construction material pipelines

The pipeline network through which natural gas is transported in the Netherlands consists of pipelines made of various materials. Within the HTL, materials other than the RTL are used. This is because within the HTL the material must meet different pressures and boundary conditions to guarantee the security of the network. The requirements that the material must meet within the natural gas network are written in NEN Standards and various laws referred to in section 4.3.1 and discussed (Gaswet, 2000). Nowadays, most gas pipes are made of steel or plastic. In the past, grey cast iron or asbestos cement was used to lay gas pipes in the ground for the low-pressure network. These materials are known to be sensitive to soil rudders, they are known to be sensitive to subsidence in the ground and this can cause pipes to become weaker (Stedin Et Al, 2019). For this reason, the regional network operators are busy replacing these pipes. Research has shown that the network mainly uses the following materials for the gas pipelines. Within the HTL, the pipelines are mainly made of steel, within the RTL gas pipes are also used that are made of various plastics (Ministery of Economic Affairs, 2017). At closures and connection points, rubbers are used to keep the network gas-tight, which rubbers are also shown in table 8, as is the materialization of the pipelines in the natural gas network in the Netherlands.

	Types of material gas pipelines				
Polyetheen	**Polyvinylchloride**	**Polyacetaal**	**Rubber**	**Steel**	**Stainless steel**
HDPE 63	PVC/CPE	POM	NBR	ASTM A 106 GR. B	AISI 316 L
HDPE 80			SBR	API 5L gr B	316 TI
HDPE100				St 37-235	

Table 8: Types of pipeline materials natural gas network **(KIWA, 2018)**

4.1.3.1. Temperatures

Within the HTL, a maximum gas temperature of 50 ° C is used. The minimum temperature against which the steel pipes in the HTL can withstand vary between -20 ° C and -10 ° C. The operation of pipes below 0 ° C suppliers of coating companies do not recommend because this can cause problems concerning the coating. An average injection temperature of natural gas of approximately

7° C is taken into account (Services, ontwerp uitgangspunten transportsysteem , 2014). For pipes that are part of the RTL, a fixed gas temperature of 7 ° C is assumed.

4.1.3.2. Pressures

Natural gas is brought under high pressure by the producers and traders into the HTL pipelines. To enable transport over vast distances, the gas is kept at the desired pressure utilizing compressor stations. Different pressure classes apply to the HTL than the RTL; this is because more natural gas is transported within the HTL over a longer length. The pressure classes within the HTL differ per route, with a maximum pressure of 67.2 bar, 71.6 bar or 80.9 bar (GTS, 2017). The maximum network pressure of the RTL system is 41 Bar with a minimum network pressure of 16 bar. The low-pressure system managed by the regional network operators means that the pipelines have a working pressure of under 16 bar for the pipelines that serve the natural gas transport.

4.1.3.3. Internal diameter

Within the HTL, pipelines are used that vary in internal diameter, and these vary from 105mm to pipelines with an internal diameter of approximately 1200 mm for the transport of natural gas. For the RTL, other dimensions apply for the internal diameter of the natural gas pipes; these vary from 105 mm to 445 mm (Gasunie main gas network, 2014).

4.1.4. Potential material risks

Because this research examines whether the natural gas pipeline network is suitable for the transport of hydrogen via the existing network, it must be examined what risks arise in the field of degradation and failure mechanisms of materials within the network. Several risks have already emerged that relate to the fire and explosion hazard associated with hydrogen and how these risks relate to the existing natural gas network.

The main risk that has emerged is the leak-tightness of the network; this relates to the pipelines' materials. Research shows that this is more important for plastic components such as O-rings, gaskets, membranes, etc. than for steel pipelines. Uptake and diffusion of hydrogen will be different (higher) than for natural gas. For example, the permeation of hydrogen through PolyEthylene (PE) is five times higher for hydrogen than natural gas (C.S. Marchi Et Al, 2017). Although this naturally leads to a slightly higher volume loss of gas, the energy loss is not much more significant, and overall the loss is still negligible. This is not seen as a problem, but must be adequately documented. Research has shown that hydrogen, unlike natural gas, can lead to hydrogen embrittlement. Hydrogen can also influence the fatigue behavior of steel and, for that reason, influence the life of pipelines that are operated under varying pressures. Material fatigue depends on: Pipeline material, Construction, and Pressure / Pressure changes (F. Tabki Et Al, 2008).

To prevent internal corrosion and erosion, clean and dry gas must be transported. This not only applies to hydrogen but also natural gas, and other mixed dry gas means that the water dew point must remain below 60% relative humidity during all conditions (SD Paul Et Al, 2013). Natural gas pipes must meet the guidelines against crack propagation. For this reason, natural gas pipelines are designed to stop a break within a limited pipeline length. A prerequisite for the crack stop is that the gas decompression rate is higher than the travel speed of the crack in the pipeline (M. Melaina Et Al, 2013). The decompression rate is related to the speed of sound in the medium. Hydrogen is 3x higher in sound speed than natural gas. This has a favorable effect on the crack stop in the event of a pipe break (Arcelor Mittal, 2016).

4.2. Transport capacity, Compression and Reduction

It is essential to know for the existing natural gas network what the transport capacity of hydrogen is concerning natural gas. This is to indicate the amount of energy the natural gas pipeline network can transport in the form of hydrogen molecules. The energy content of hydrogen is approximately 12 MJ/Nm3 compared to 35 MJ/NM for low calorific natural gas. To meet the same energy needs as natural gas, hydrogen must transport three times the volume. Pressure drop is the critical parameter for dimensioning a pipeline network, and the most crucial parameter for this, in this case, is the density of hydrogen relative to natural gas. Research has shown that two types of compressors are used within the current gas network, piston compressors, and centrifugal compressors. There are differences in the compression of natural gas and hydrogen. Hydrogen requires compression of 3 times the volume for the same energy content (S. Kneck Et Al, 2017)In the compression and reduction of gases, the Joule-Thomson effect plays a role in the temperature change of gas. With pressure reduction with natural gas, the temperature of the gas will drop by a 0.5 ° C / bar pressure drop. With a pressure drop from 80 to 20 bar, the temperature will drop by 30 ° C. Conversely, the temperature rises with compression. With hydrogen, the temperature during pressure reduction rises by 0.035 ° C/bar pressure drop. With a pressure drop from 80 to 20, the temperature of hydrogen will increase by 2.1 ° C (Ministery of Economic Affairs, 2017).

4.3. Laws, Regulations and natural gas transport standards

Due the liberalization of the gas market the Dutch government officially introduced the “Gaswet”. This encompasses the legal framework that apply in the field of gas transport and supply and implements the EC Directive that applies to the intern European gas market dating from 1998. The

Gas Act is a law of the Ministry of Economic Affairs. Within the Gas Act, quality requirements have been laid down in accordance with the regulation on quality aspects of grid management for electricity and gas (MRQ). According to the Dutch law every 2 years, a grid operator must publish a capacity plan following Article 8 of the Gas Act. This contains the total requirement of the capacity of the transport and how this must be met over 7 years (Gaswet, 2000). Based on the gas law, a minister can instruct the network operator to make certain provisions if the total need for capacity for the transport of gas is insufficiently or inadequately met. The minister can apply administrative enforcement to achieve this. The rules surrounding capacity plans that apply to network operators are defined in the “Capacity Management Scheme for Gas Management Network Plan”. The capacity plans are mainly focused on the quality dimension of transport security and are less focused on safety. The capacity plan is based on the principle that the transport security of the network must be able to meet a capacity demand from the market during a severe winter (Gaswet, 2000). Network operators must also indicate which maintenance method is used and the quality assurance system (ISO) has been applied to the management of the network. The responsible authority for the capacity and quality plan of network operators is within the Netherlands the government institute of Authority consumers and market (ACM).

The External Safety Pipelines Decree (Bevb) contains risk standards concerning external safety that operators with pipelines containing hazardous substances must comply with. In the External Safety Pipeline Regulations (Revb), rules have been set concerning the calculation of the risks of the pipeline (Gas Act, 2000). This scheme is subdivided into different modules. Natural gas falls in module B "High-pressure natural gas pipelines" and hydrogen in module D "Chemical pipelines". The result that the calculation values that may be used for risk calculations for hydrogen differ from those for natural gas (ACM, 2019). Based on long-term experience with natural gas pipelines in the Netherlands and the statistics derived from this, the probability of failure to be charged for a pipeline is lower when it transports natural gas than when the same pipeline is used for transport hydrogen. The higher failure probability for hydrogen transport leads to an increase in the risk contours. The current regulation advises having calculations carried out (with Safety and Pipesafe) to quantify the difference, taking into account the difference in consequences of natural gas and hydrogen outflow. These regulatory aspects need to be resolved before large-scale use of hydrogen can replace natural gas (Ministery of Economic Affairs, 2017).

standards, guidelines and relevant regulations	
European regulations	
Directive	Low voltage
Directive	EMC
Directive	Gas appliance
Directive	Pressure equipment
Directive	ATEX
Directive	Machinery

Table 9: Standards, guidelines and relevant regulations for natural gas distribution **(Gasunie hoofdgasnet, 2014)**

Natural gas pipeline installations	
Activities degree environmental management	General rules environmental management
Activities regulations environmental managment	Regulation general rules environmental management
ARBO	Working condition law
BEVB	External pipeline safety decision 2011
BEVI	Decree on external security of establishments
BRZO 2015	Decision risks of serious accidents 2015
NEN 1059	Requirements for gas pressure regulating and measuring stations with an inlet pressure lower than 100 bar
NEN 1091	Safety requirements for steel gas pipelines with a design pressure higher than 1 bar and lower or equal to 16 bar
NEN-EN 1775	Gas pipes in buildings max working pressure 5 bar
NEN 3650	requirements for steel transport pipes
NEN 3651	additional requirements for steel pipes in junctions with important water management works
NEN 3655	safety management system for pipelines for the transport of dangerous gasses
NEN-EN 12186	gas supply system - gas pressure control stations for gas transport and distribution functional requirements
NEN-EN 12954	Cathodic protection
NEN-EN 13509	Measurement techniques of cathodic protection
NEN-EN 14505	Cathodic protection of compexe constructions
NEN-EN 15001	Gas installation pipes with operating pressures greater than 0.5 bar for industrial and non-industrial gas installations
NPR 2760	Mutual influence of pipelines and high-voltage connections
NPR 6912	Cathodic Protection
NTA 8120	Asset management requirements for safety, quality and capacity management system for electricity and gas management
NTA 8620	Specification of a safety management system for risksmajor accidents
Wabo	Environmental Law General Provisions Act
Pressure Equipment Commodities Act Decree	Pressure Equipment Commodities Act 2016
Wion	Underground Network Information Exchange Act
Wrm	Laws of environmental Conservation
Wro	Spatial Planning Act

Table 10: standards, guidelines and relevant regulations for natural gas installations **(Gasunie hoofdgasnet, 2014)**

4.4. Chapter Conclusion

The main natural gas and regional network within the Netherlands works as follows; the main natural gas network in the Netherlands consists of 2 separate pipeline networks that run parallel to each other. The HTL is linked to the RTL, networks of other transmission system operators, producers, storerooms, and large domestic end-users. Power plants, industries, and the networks of the regional grid operators are linked via gas receiving stations. The HTL thus feeds the RTL. On the exit side, the RTL is linked by a gas receiving station to low-pressure networks. The main installations within the network are the compressor stations responsible for keeping the natural gas network under pressure to enable gas transport. Within the network, two types of compressors are used, piston compressors and centrifugal compressors. Gas receiving stations form the link between the HTL, RTL, and the transport network of regional network operators. The main task of a GOS is to reduce the transport pressure and measure the amount of natural gas supplied. The most important part of the natural gas network in the Netherlands is the pipelines. Different materials are used in the for the gas pipes, the most common materials being Steel and Plastics. Table 8 shows correctly which materials are used for the regional- and main gas pipelines.

Chapter 5. Technical and Economic feasibility

5.1. Technical feasibility

The technical feasibility assessed whether the existing natural gas pipeline network is resistant to hydrogen. This is being investigated in several aspects, and these aspects emerged from the hydrogen risk analysis. The minimum conditions for integer hydrogen distribution through pipelines have emerged. Besides, research has been conducted into aspects that determine the quality of gas pipelines. Several aspects have emerged from this study that determines the technical quality of a pipeline. The investigated aspects are Material fatigue, Permeation, hydrogen embrittlement, leakage risks, and erosion of pipes. Natural gas has different properties than hydrogen, which means that the material of which the gas pipes are made can behave differently. This can cause the quality of the gas pipes to deteriorate or make it entirely unusable for hydrogen. In addition to investigating the materials of the pipeline, research was also conducted into whether the natural gas compressors are suitable for hydrogen and what the network's capacity will be if hydrogen is transported instead of natural gas.

5.1.2 Material resistance hydrogen gas

In the European research project NATURALHY, various metals were investigated concerning the applicability of the gas network for the transmission of hydrogen molecules (NATURALY, 2010) Different types of steel were examined under different conditions: pressure, varying mechanical stresses, and fatigue. To guarantee the experiment's quality, conditions have been created that are comparable to the useful life of 40 years, which is used in practice. Hydrogen is widely transported and used in the petrochemical industry. The extensive scientific literature on this is available on the effects of hydrogen on materials. The regional gas network has, through practical tests, made an overview of the influence of hydrogen on this network concerning materialization (Stedin Et Al, 2019). A multi-year study called the EDGaR has been conducted in the Netherlands, in which no tests have been carried out with syngas, which contains 62% of hydrogen. A conscious choice was made for 62% hydrogen instead of 100% because scientific literature provides sufficient information about hydrogen distribution and materials' influence. A practical study was carried out in Denmark in which 100% hydrogen gas was transported for ten years through used and new PE and steel pipes. (H.Iskov Et Al, 2017). From international scientific research, a clear picture has been obtained of the effects of 100% hydrogen distribution on material and the failure mechanisms.

5.1.2.1. Plastic material

The primary plastics that occur in the natural gas network are Polyethylene (PE), Polyvinyl chloride (PVC), Polyacetal (POM), and the rubbers NBR and SBR. This includes piping material and the rubbers that are important for seals in connections within the spike gas network at the valve, and parts for pressure regulators and gas meters. (KIWA, 2018).

Hydrogen can affect plastics because they can react chemically with hydrogen, and there is a chance that they will change due to their physical properties due to adsorption or swelling (E. Baur Et Al, 2016). The material's sensitivity to hydrogen depends on several factors, such as pressure, temperature, gas composition, and duration. Much scientific literature is available on this subject, and many practical studies have been carried out, from which certain things can be concluded that relate to plastic and the influence of hydrogen,

It can be concluded from the books of the ISO / TR7620 that hydrogen has nothing to a negligible amount of influence on the rubbers SBR and NBR (7620 ISO/TR, 2005). MDPE, HDPE, and PVC has been tested for a short duration of approximately 60 days for the influence of 100% hydrogen on these materials. E. Baur concluded from research that hydrogen has little or no influence on the mechanical properties of the above plastics. Mass and volume measurements also show no changes (E. Baur Et Al, 2016). The aging of PE 80 and 100 has been investigated at a gas pressure of 100 bar where there are gas mixtures of natural gas and hydrogen up to 100% hydrogen. It was concluded from this that both PE types are resistant to hydrogen (NATURALY, 2010). In Ameland, in practice, plastics PVC, PE100, POM, NBR, and SBR were exposed to a gas mixture of up to 20% hydrogen for four years, no differences in material properties were found (M. Kippers Et Al, 2012). From research conducted by Kiwa Gas Technology into the resistance of POM to hydrogen, no significant changes were found both physically and mechanically. The International Gas Union has researched PE, whereby pipes were removed from the gas network exposed to natural gas for four years, during which the pipes were exposed to 4 bar hydrogen for ten years. From this, it can be concluded that hydrogen does not affect the aging of PE 100 material (S. Kneck Et Al, 2017).

5.1.2.2. Steel Material

Metals can deteriorate in quality and degrade with this, which can occur if it comes into contact with hydrogen. Critical failure mechanisms, such as changes in tensile strength, fatigue, and embrittlement, have been considered from research into existing literature and several field studies. (KIWA, 2018). Over the years, various steel types have been used within the network, used in pipes, fittings, and other components. These are shown in Table 8 in literature studies have been found on different types of steel in studies and handbooks (API 5L/ISO 3183, 2009). The steel ASTM A106 gr B.

its properties are equivalent to API 5L gr. B and reasonable to API 5L gr. X42 (x70). The main difference between the two steel grades is that B may have a lower yield strength for B 245 MPa and for X42 290 Mpa. The maximum elongation and tensile strength are equal, with the B allowing the pipeline to have a welded seam. API 5L gr. X70 is a comparable but more modern type of steel (Arcelor Mittal, 2016).

Degradation of the mechanical properties and associated fracture mechanisms can differ per material and per gas composition. The extent to which hydrogen influences the fracture mechanisms determines whether the natural gas network is suitable for hydrogen. Various studies and literature have shown that strong samples are sensitive to this form of embrittlement (S.D. Paul Et Al, 2013). What occurs with hydrogen embrittlement is an effect that converts molecular hydrogen into atomic hydrogen. The atomic hydrogen dissolves in the metal and diffuses through the metal. Atomic defects in the metal can cause atomic hydrogen to form and form molecular hydrogen. Molecular hydrogen is hardly able to diffuse through the metal and is thus trapped. There is a risk that, due to the uneven stress distributions in the material, embrittlement will eventually occur (D.H. Hering, 2010).

Hydrogen has high Dissociation energy, which means that much energy is needed to form atomic hydrogen. This process therefore only occurs at high temperatures or electrical discharge (W.l. Jolly, 2017)The natural gas network temperatures are too low, and the electrical charges are so minimal that hydrogen embrittlement is not to be expected. Electrochemical processes can also generate atomic hydrogen, so only dry hydrogen gas must be transported (KIWA, 2018). In the NATURALHY where up to 62% hydrogen was added to the natural gas, the influences of hydrogen on different types of steel X70 and x50, including welding, the experiments were carried out so that they correspond to the service life of 40 years for pipes. These studies have shown that hydrogen embrittlement has not occurred. Within the national network, the compressors powered by gas turbines are fed with gas from the network. Changing the gas also changes the fuel quality. High temperatures can occur around 1200 degrees within these gas turbines. This may be sufficient to dissociate hydrogen and cause hydrogen embrittlement (NATURALY, 2010).

The mechanical properties of the materials of different types of steel have been investigated. The test was carried out with hydrogen under a 69 bar pressure at room temperature compared to the standard conditions. For steel grades A106 gr. B., X42, and X70 hardly any differences were noted.

However, the elongation at A106 gr. B 21% smaller. The other differences are shown in Table 11 below.

Steel grade	mechanical characteristics	Air	69 Bar H2	Difference (%)
A106 gr. B	*Upper Yield stress (MPa)*	462	503	8.9
	Tensile strength (MPa)	559	576	3.0
	elongation at break (%)	14	11	-21.4
X42	*Upper Yield Stress (MPa)*	366	331	-9.6
	Tensile Strength (MPa)	511	483	-5.5
	Elongation Yield Stress (%)	21	20	-4.8
X70	*Upper Yield Stress (MPa)*	584	548	-6.2
	Tensile Strength (MPa)	669	659	-1.5
	Elongation Yield Stress (%)	20	20	0.0

Table 11: Mechanical characteristics of steel pipelines **(NATURALY, 2010)**

The fracture toughness says something about the resistance of the material to fracture growth. The gas composition, applied voltage and gas pressure are decisive for this (C.S. Marchi Et Al, 2017). Pure methane was used during the tests, from which it was concluded that the fracture toughness for X70 at 69 Bar decreased by about 50% to a value of 95 MPa 1/2. According to researchers, this is still well assessed, so the material is still considered suitable. This corresponds to the tests that were carried out during the NATURALY project (NATURALY, 2010). Fatigue says something about the occurrence and rupture of a fracture under the influence of a cyclic load. Hydrogen generally accelerates the crack growth of metal. However, this is partly dependent on the gas composition. This can be countered by adding oxygen to pure hydrogen (H.Iskov Et Al, 2017).

5.1.2.3. copper, cast iron, aluminium

Few scientific studies are available on the influence of hydrogen on cast iron. Handbooks and guarantees from the supplier have shown that they all guarantee their cast iron product's quality against exposure to hydrogen and a possible chemical reaction (NATURALY, 2010). Within the natural gas network, the materials aluminium and copper are used for connecting pipes. At the same time, aluminium is mainly used in pressure regulators and gas meters. A practical study has exposed these materials for four years to a gas mix of hydrogen and methane with a maximum of 20% hydrogen. This research has shown that hydrogen has no influence on the effect and physical properties of copper and aluminium (KIWA, 2018).

5.1.3. Transport capacity, Compression and reduction

Natural gas has more energy content than hydrogen per M3, for L-gas an energy content of 35MJ / M3 and hydrogen 12MJ / M3. To transport the same amount of energy as natural gas, three times the volume of hydrogen is needed. Research has shown that the density of hydrogen is a factor of 9 smaller than natural gas. Because the pressure drop is inversely proportional to the square root of the density, a flow rate of hydrogen with a volume three times greater than natural gas has approximately the same pressure drop (H.Iskov Et Al, 2017). However, other parameters vary with pressure or flow rate, thus influencing the pressure drop or transport capacity. Research shows utilizing detailed calculations that an existing gas pipeline, with constant pressure drop to conversion to 100% hydrogen gas, can transport 98% of the energy compared to low-calorific Groningen natural gas and 80% for high-calorific natural gas. Hydrogen requires compression of 3 times the volume for the same energy content (S. Kneck Et Al, 2017). Because of this fact, centrifugal compressors require a 1.74 times higher rotation speed than natural gas for the same pressure build-up. The centrifugal compressors are not designed for this (Ministery of Economic Affairs, 2017). The fact that hydrogen is a factor 3 smaller in molecule than natural gas can also cause problems for the compressor stations. With reciprocating compressors, the type of gas is less critical. However, good research must still be done with these compressors to see whether they are suitable for 100% hydrogen distribution.

5.1.4. Risk of leakages

Leakage from connections (both outside and inside) and any further consequences pose a risk to all piping systems that distribute combustible gas. In small gap leaks, the flow is laminar at distribution pressures. This means that the volume flow, at a given pressure, is inversely proportional to the dynamic viscosity of the gas. The viscosity of hydrogen is 0.88 10-6 Pa.s. That of methane is about 25% higher: 1.10 10-6 Pa.s. The conclusion is that a possibly leaking connection in a hydrogen network is about 25% higher in terms of volume flow compared to the same leaking connection in a natural gas network (W.l. Jolly, 2017). This difference is hardly significant from a safety point of view; the more so since the leak's energy content is more than half smaller. A point of attention remains the lower ignition energy and the more excellent concentration range of the combustible mixture. Experts indicate that this does not cause significant leak-tightness problems for the system (API 5L/ISO 3183, 2009).

5.2. Economic feasibility

The economic feasibility is used to analyze whether the investments that need to be made to make the network suitable for hydrogen distribution are economically viable. The economic feasibility is just as important as the technical feasibility of hydrogen gas transport through the existing network. Suppose hydrogen, like natural gas, wants to contribute to the energy system in the Netherlands in the future. In that case, it is necessary to create a hydrogen market that works in a liberalized manner, just like the natural gas market. This is only possible if hydrogen becomes commercially interesting for producers and sold to consumers at competitive prices.

5.2.1. Investment costs

Research conducted by KIWA gives an indication of the investments that must be made to make the natural gas pipeline network suitable for hydrogen gas transport. From a technical perspective, it can be stated that the HTL and RTL pipelines do not undergo degradation if hydrogen is transported instead of natural gas. Also, in the field of safety, in which the risks of leaks in hydrogen distribution have been tested, no remarkably increased risks have emerged. Based on these findings, it can be stated that the investments that must be made to make the natural gas network suitable for hydrogen gas distribution can remain relatively low. Research by KIWA commissioned by network management Netherlands shows that the costs of adapting the existing natural gas network to hydrogen cost approximately an investment of € 700,000,000 (KIWA, 2018). The costs are divided among the following focus areas:

- Safety of transport distribution
- Security of supply and lifespan
- Feed-in
- Safety in delivery and end-use
- Adjustments to installations at the end user

The following cost items have emerged for safety for transport and distribution. These are shown in tables: 12, 13 and 14, in which a distinction is made between larger cost item (++), limited cost item (+), no-cost (-). The technicians will have to be retrained for working with hydrogen. Course material must be developed for this (KIWA, 2018). The development costs for this are estimated at approximately € 200k. Work on the hydrogen distribution network requires procedures and measures to be able to work safely. These measures and procedures make annual maintenance of approximately 10% more expensive than current network maintenance costs. New norms and standards must be developed that relate to hydrogen distribution networks. This requires a one-off extension/revision of existing standards (TNO Energievisie 2030, 2019). Digging damage can potentially pose an increased risk. It is, therefore, necessary to apply increased supervision during excavation work. This can amount to a cost of 200M € / yr if a 100% check is required.

Measure	One-time Basis	once per home equivalent	recurring every year	recurring per home equalivent
1. Safety Transport and Distribution		€/WEQ	K€/JR	€/(jr WEQ)
Information/training technicians	++	+	-	-
Adapt work procedures maintenance / construction	-	-	-	10
Supervision of excavation	++	-	-	+

work				
Automatic sectioning of the gas network	++	+	-	+

Table 12 Investments Costs Hydrogen Transformation 1. **(KIWA, 2018)**

For life security and feed-in, the following investments must be made to ensure this if hydrogen gas is distributed instead of natural gas. Research has shown that investments need to be made in personal protective equipment; this concerns equipment for rinsing pipes with inert gas. The equipment used for detecting leaks also needs to be replaced with a suitable variant for hydrogen. These costs must be incurred in the transition phase and are estimated at approximately € 1000 per employee. Additional control of the contaminants in the hydrogen gas should also be done if the end-user uses hydrogen insensitive fuel cells. This amounts to 25K € per 1000 / 10,000 WEQ (housing equivalent) according to estimates made by KIWA (KIWA, 2018).

Measure	One-time Basis	once per home equivalent	recurring every year	recurring per home equalivent
2. Security of supply and infeed		€/WEQ	K€/JR	€/(jr WEQ)
Adjustments to tools and measuring instruments	-	+	-	-
Contamination control	-	-	-	+

Table 13 Investments Costs Hydrogen Transformation 2. ***(KIWA, 2018)***

In addition to the technical requirements, the end-user must be made aware of hydrogen and how this gas has different properties than natural gas. This can be done through advertising and information campaigns. Topics to be addressed here are odor difference, absence of CO poisoning, and abnormal hydrogen behavior in the event of leakage. It is important that hydrogen in the field of hydrogen safety perception that odorization is applied. Hydrogen is expected to have a different odor than natural gas, which requires adjustments to the odorization installations. This is estimated at 100 * 10 k € / 10 MWEQ. Because hydrogen has a higher risk perception than natural gas, it is recommended that more odorisation points should be installed within the system. KIWA indicates that more expensive couplings and additional tightness tests must be used for gas within installations. A hydrogen molecule is more likely to escape through a leak in a system than natural gas. This entails an increase of approximately € 10 per installation per WEQ. Research by KIWA indicates that the gas meters within the network need to be adjusted. When switching to hydrogen, larger volumes have to be transported to deliver the same energy.

Measure	One-time Basis	once per home equivalent	recurring every year	recurring per home equalivent
3. Safety of delivery for end-users		€/WEQ	K€/JR	€/(jr WEQ)
Advertising/ information	++	+	-	-

campaign				
Adjustment of odorisation	++	+	-	-
Extra check odorisation	-	-	-	+
Adjustment of standards for leak-tightness	++	-	-	-
Adjustment work procedures, construction and maintenance for gas installations	-	-	-	+
4. Adjustments installations domestic end-users		€/WEQ	K€/JR	€/(jr WEQ)
New gasmeters	-	+	-	-
Extra control gas installations (domestic)	-	-	-	++
Adjust appliances (boilers)	-	++	-	-

Table 14 Investments Costs Hydrogen Transformation 3. ***(KIWA, 2018)***

Within this research, the elements are assessed that are necessary for a properly functioning regional and main gas pipeline infrastructure. The costs incurred for adaptations to the installations at the end-user are therefore not relevant for the research's technical feasibility but are essential for the economic feasibility. Besides, it has also emerged that the compressors in the network are not always suitable for hydrogen distribution. This can result in a cost item and, for that reason, impact the investment required to make the network suitable for hydrogen. It has been concluded from interviews that before hydrogen can be transported through a natural gas pipeline, the gas pipelines must first be cleaned and checked. This can also entail additional costs on top of the 700,000,000 euros. If it is concluded from further research that the compressors are not suitable for hydrogen, they must be replaced.

In order to determine whether the investment that must be made to make the natural gas network suitable for hydrogen distribution, it is crucial to know the value of the network. GTS's annual accounts have revealed the value of the main and regional networks. To determine the total value of the network, all installations are also included in the calculation. Table 15 showed that the network represents a total of 5.9 billion euros. Research by KIWA has shown that the transformation to hydrogen will cost 700,000,000. Many costs are not for technical adjustments to the network but for adjustments in the field of standards, work instructions, and installations in the home. Only if the compressors have to be replaced can this entail a high-cost item. Since these have represented a value of 1 billion euros at purchase, if the entire compressor station has to be replaced, this is a significant investment.

Tangible fixed assets *(In Million euro's)*	Book value as of Dec.31 2019	Purchase value as of Dec. 31 2019	Cumulative depreciations as of Dec.31 2019
Compressor stations	€ 553,7	€ 1.006,3	€ - 452,6
Installations	€ 762,0	€ 1.484,1	€ - 722,1
Main transport piping line network	€ 3.692,5	€ 5.315,1	€ - 1.622,6
Regional transport piping line network	€ 882,2	€ 1.192,1	€ - 309,9
Total net worth:	€ 5.890,4	€ 8.997,5	€ - 3107.2

Table 15 Regional- and Main Natural gas network Value **(Services, Jaarrekening, 2019)**

5.2.2. Feasibility and Potential Dutch hydrogen market

Research done by the University of Groningen "Outlook for a Dutch hydrogen market" by Machiel Mulder has revealed three crucial economic factors crucial for the development of a hydrogen market (Machiel Mulder Et Al, 2019). These factors are the density of the international natural gas market, the degree of stringency of national and international climate legislation, and electricity price. Crucial to whether hydrogen is economically feasible and can contribute to a sustainable energy system is the question to what extent green hydrogen can be produced on a large scale furthermore if this price is in line with the market. If the Netherlands wants to set up a market for this, green hydrogen must compete with gray hydrogen. Research by the University of Groningen has highlighted three aspects that are crucial for this: Price of natural gas, the electricity price, and climate policy (IRENA, 2018). The potential of hydrogen is excellent, it can replace methane for a large part and can be easily stored and transported via pipelines. Only if natural gas becomes cheap by tapping new fields is government support necessary to make it competitive. CO2 Prices, taxes on natural gas, and events on the international natural gas market are all critical for the feasibility of hydrogen. Machiel Mulder indicates that at a CO2 price of 30 euros, blue hydrogen becomes cheaper than gray. If this is achieved, investments will come naturally. Hydrogen as an energy carrier needs public support to become successful. Research has shown that Dutch society does not yet trust it. In order to contribute to a sustainable energy system in the Netherlands, the hydrogen must be generated sustainably. Research shows that green electricity is scarce, and therefore large-scale production of green hydrogen is not yet feasible. The construction of wind farms and installing solar panels will bring a substantial and growing amount of sustainable electricity onto the market in the coming years. As is known, the generation thereof proceeds with peaks and troughs. Sometimes there are surpluses; sometimes there is too little. Sustainable hydrogen production is an attractive solution for buffering those surpluses. However, that does affect the energy mix. (Machiel Mulder Et Al, 2019).

To determine whether the investment that must be made to make the natural gas network suitable for hydrogen distribution, it is crucial to know the value of the network. GTS's annual accounts have revealed the value of the main and regional networks. To determine the total value of the network, all installations are also included in the calculation. This showed that the network represents a total of 5.9 billion euros. Research by KIWA has shown that the transformation to hydrogen will cost 700,000,000. Many costs are not for technical adjustments to the network but for the field of standards, work instructions, and installations in the home. Only if the compressors have to be replaced can this entail a high-cost item. Since these have represented a value of 1 billion euros at purchase, if the entire compressor station has to be replaced, this is a significant investment.

5.3. Chapter Conclusion

The main and regional pipeline network consists mainly of materials steel and plastic. Prolonged pressurized hydrogen gas distribution does not significantly affect the degradation of the materials. The materials have been tested for critical failure mechanisms. For plastics, this was mainly the aspect to what extent a chemical reaction with hydrogen can occur. Research has shown that this is not the case with hydrogen distribution through plastic pipelines. Steel has been tested for: tensile strength, metal fatigue, and embrittlement. Research shows that hydrogen gas under simulated conditions has no significant influence on these aspects. In the field of leak tightness, it has emerged that the difference between hydrogen and natural gas is not significantly higher, so practice teaches us that the risk does not increase with hydrogen because the energy density of hydrogen is lower than natural gas. A point of attention remains the lower ignition energy and the higher concentration range of the combustible mixture.

Hydrogen is a factor of three smaller than natural gas, to transport the same amount of energy as natural gas, three times as much volume is needed. Thus, the centrifugal compressors within the main and regional networks are not necessarily suitable for hydrogen gas. In the field of materials, the natural gas network is suitable for hydrogen in the field of installations; this is not the case. Adjustments need to be made to prepare the natural gas network for hydrogen.

The technical adjustments that must be made to adjust the network mainly relate to adjusting working methods, safety adjustments, legislation and regulations, gas meters, cleaning pipes. The costs for this are estimated at € 700 million. If it later turns out that the compressor stations are not suitable and they need to be replaced entirely, an additional investment of 1 billion euros is added. The economic feasibility should take into account the feasibility of hydrogen as an energy carrier itself because if this technique is not feasible, an investment in the hydrogen network has no economic feasibility at all. The investment that must be made to make the network suitable for hydrogen is only economically feasible if green energy exists in surplus, and a profitable green hydrogen market can thus be created.

Chapter 7. Conclusion & Discussion

7.1. Conclusion

This research aimed to assess to what extent the current natural gas main and regional pipeline network is suitable for hydrogen gas distribution. The literature study results and the interviews show whether transforming the natural gas pipeline network is technically and economically feasible. This research has provided an accurate picture of the technical and economic feasibility. Thus, it indicated how the natural gas network could contribute to a sustainable energy system by transporting a cleanly produced energy carrier hydrogen instead of fossil fuel like natural gas.

The research results have shown that hydrogen has a number of characteristic differences compared to natural gas. Hydrogen is a factor three smaller than natural gas. Also, hydrogen requires 13.5 less energy to ignite. Finally, hydrogen is lighter than natural gas, and for that reason, it spreads quickly in small spaces and has no odor. From these results, technical conditions have emerged that hydrogen distribution through pipelines must meet. A technical condition is that higher technical requirements must be set for the network's leak-tightness because the risk profile of hydrogen is higher than that of natural gas. Also, a technical condition is that this ordorization must be applied better to detect hydrogen gas in the event of a leak. New laws and regulations also need to be designed around hydrogen distribution to meet the minimum conditions for natural gas.

The regional and main natural gas network consists of two separate pipelines that run parallel to each other. Gasunie Transport Services manage these networks. The Main Transport Network is linked to the regional network utilizing gas receiving stations. The main network works as the main transport network feeds the regional transport network. On the exit side of the regional network, gas receiving stations are linked to supply natural gas to the low-pressure networks managed by regional network operators. The primary installations within the network are the gas receiving stations that ensure the lowering of the transport pressure and measure the amount of gas supplied. The compressor stations increase the pressure within the network so that gas transport can take place over longer distances. Results show that the primary materials used for gas pipes are steel and plastics. Table 8 shows precisely which type of steel and plastics are used within the network.

Results show that long-term hydrogen distribution through the gas pipes made of the same materials as the regional and main natural gas network has no significant effect on the degradation of the used materials. The materials have been tested for critical failure mechanisms and subjected to tests equivalent to real-world conditions for hydrogen distribution. It can be concluded that there is no chemical reaction with hydrogen in plastic pipelines. This had emerged as a risk of hydrogen gas transport through plastic pipelines. Research shows that hydrogen can influence the degradation of metals.

For this reason, it has been investigated to what extent this money is used for the steel pipelines used in the Dutch natural gas network. Research has been conducted into the influence of hydrogen gas in steel on aspects such as Tensile Strength, metal fatigue, fracture toughness, and embrittlement. Research shows that hydrogen under simulated conditions has no significant influence on these aspects. Therefore, it can be concluded that the steel used in the network is resistant to hydrogen. In the field of leak tightness, it has emerged that the difference between hydrogen and natural gas is not significantly higher. The lower ignition energy and greater concentration range of the combustible mixture remains a point of attention. Hydrogen is a factor of three smaller than natural gas, in order to transport the same amount of energy as natural gas, it must move three times as much volume. Thus, the gas meters used in the network are no longer usable and must be replaced. The centrifugal compressors within the main and regional network are also not necessarily suitable for hydrogen gas for the same reason. From this, it can be concluded that it is technically feasible to make the regional and main natural gas network suitable for hydrogen gas.

Adjustments must be made to make the regional and main natural gas network suitable for hydrogen gas. These mainly relate to the adaptation of working methods, safety adjustments, legislation, gas meters, and pipes cleaning. This is estimated at € 700 million. If it later appears that the compressor stations will have to be replaced in their entirety, an investment of 1 billion will be added to this. Based on the purchase value of compressor stations for natural gas. These adjustments are economically feasible because research shows that the network costs due to these adjustments only need to increase by 5% per user based on the 700 million. The adaptation is economically feasible, but the feasibility of hydrogen as an energy carrier must be taken into account. Because research shows that hydrogen only becomes economically viable when green electricity exists in surplus. Thus, a profitable green hydrogen market can be created that functions like the liberalized natural gas market. From this, it can be concluded that the investment in the transformation of the regional and main natural gas network for hydrogen gas is only economically feasible if green hydrogen can be produced sustainably on a large scale.

7.2. Discussion

Following the climate agreement in which it is described that the Netherlands will start with the systematic phasing out of natural gas. The natural gas network in the Netherlands is a finely meshed network that meets high-quality requirements. Within this research, the focus is primarily on whether the contemporary main and regional natural gas network is suitable for an alternative sustainable energy carrier; in this case, hydrogen. The main goal is to gain insight into what hydrogen is, how the regional and main natural gas network works, and whether the materials in the network are suitable for hydrogen. In addition, an indication has been made of the technical transformation costs and whether this is economically feasible together with hydrogen. Before the study, the material whose gas pipelines were expected to be hydrogen resistant. This was from the literature of the petrochemical industry with extensive experience in large-scale hydrogen distribution through gas pipelines. Research has shown that this is the case. Within this research, a conscious choice was made to focus on the regional and main natural gas pipeline network. This was done because the time frame was limited, and the research had to remain specific. It was also decided to focus specifically on materialization and not on gas technology because gas technology is a complex subject. The author did not know that subject before this research.

With that said, the results can be discussed. The overall conclusion of the research is that the material that makes up the main and regional natural gas pipeline network is suitable for hydrogen. Also, it has also emerged that the existing natural gas network is resistant to the most significant risks concerning the safety of hydrogen gas distribution through pipelines. It has also emerged that compressors within the network may need to be adapted. They cannot handle the capacity that must be transported to transport the same energy content as natural gas in the form of hydrogen. To determine the total technical feasibility of the network, all aspects within an installation must be tested against hydrogen, which takes much time. Because the time element within this study is limited, it was decided to focus only on the materialization and the most important aspects that emerged from the risk analysis. To get a complete picture of whether the entire network is suitable for hydrogen, certain matters such as gas technology and installations need to be further explored. This research only provides a general picture of the technical feasibility. However, it can be concluded from this that the first findings of hydrogen in the natural gas network are positive. The research results are valid when looking at what is being researched. The focus is on the material of the network. The results provide a clear picture in the field of materialization and the risks of hydrogen. The research is less valid if the total technical feasibility is considered because the entire network has to be analyzed. For the purpose and core of this research, it can be said that the research results are valid.

However, the economic feasibility must be critically examined because the capital and regional value represent a value. This value has been determined from GTS's annual accounts. Research conducted by KIWA has shown that to convert the natural gas network, approximately 700 million is required. Looking at KIWA's research, we mainly looked at how the end-user uses hydrogen. Therefore, the costs that the end-user must incur are also included in the investment costs required to make the existing network suitable for hydrogen. These investments are not for the network itself and are not directly interesting for the research. Interviews with Gasunie have revealed that the pipelines must be cleaned; these costs are not included in KIWA's investment costs. More important for the economic feasibility is whether hydrogen technology can become profitable; the efficiency of hydrogen utilizing electrolysis is on average, about 75%, which means that 25% of the electricity is lost. Also, only 15% of the total energy consumption in the Netherlands is generated sustainably. In order to make hydrogen profitable, green electricity must be available at a low price; this is not expected in the next ten years. This determines that green hydrogen will not be profitable for the next 10/15 years and is not commercially attractive. Besides, there is also a residual demand for natural gas, and for that reason, the network cannot be wholly transformed into hydrogen because there are two separate natural gas pipelines within the Netherlands. There is a chance that one gas pipeline can be transformed into hydrogen. Follow-up research should determine whether hydrogen can become commercially appealing within a considerable period and whether the development of this market can be accelerated. Further research also needs to be done on the gas technology for hydrogen gas and how it affects complex installations within the main and regional natural gas network.

7.3. Recommendations

- In renovation projects where gas pipes are replaced, use materials that are also resistant to hydrogen gas. This must be done with a view of the future-resistance of the natural gas network that it can be used in the future as a transport medium for gas.

- Do further research into whether the compressor stations are suitable for hydrogen. This should look at the centrifugal compressors and the reciprocating compressors located in the main and regional natural gas network.

- It must be considered which gas meters in the network need to be adapted because the current gas meters may be no longer suitable for the volumes of hydrogen that are expected to be transported.

- Research must be carried out for each installation. The entire installation is exposed to hydrogen for a long time to determine whether it is entirely suitable for the distribution of hydrogen gas.

- Hydrogen must be analyzed for how it behaves in pipes compared to natural gas. This is important to know whether the network can be switched entirely to hydrogen, where safety is an essential factor.

- It must be investigated how the government can contribute to accelerating the development of a hydrogen market. This should be done because it is expected that green hydrogen will not become profitable in the coming years and, therefore not commercially appealing. Thus, it is not yet possible to create a liberalized market as it does for natural gas.

- Determine to what extent blue hydrogen can contribute to accelerating the emergence of a hydrogen market. Blue hydrogen can play a role in creating supply within a market; this is crucial for developing a market.

- Europe must start promoting clean energy by increasing CO2 taxes on fossil fuels. This makes it more attractive for investors to invest in clean energy, and therefore the process can be accelerated.

- An opportunity may be to investigate the possible preparation of one of the main natural gas pipelines for hydrogen. The entire network cannot yet be converted because there will be a residual gas demand from the market in the coming decades.

References

7620 ISO/TR. (2005). *Rubber materials - Chemical Resistance.* ISO.

ACM. (2019, Feb 09). *www.acm.nl/onderwerpen/energie/wet--en-regelgeving*. Retrieved 05 10, 2020, from www.acm.nl: https://www.acm.nl/nl/onderwerpen/energie/wet--en-regelgeving/wet--en-regelgeving-energie

Ad van wijk et al. (2018). *Waterstof de sleutel voor de energietransitie.* Delft: TU Delft.

Ad van Wijk Et Al. (2018, February 14). Waterstof is het nieuwe aardgas. (A. dagblad, Interviewer)

Algemene Rekenkamer. (2014). *Besteding van aardgasbaten: Feiten, cijfers en scenario's .* Den Haag: Algemene rekenkamer.

API 5L/ISO 3183. (2009). *Petroleum and natrual gas industries - Steel pipe for pipeline transportation.* ISO 3182.

Arcelor Mittal. (2016). *Material Grade Comparison chart - Pipes.* Acelormittal.

Aue, J. j. (2018). *De rol van waterstof binnen de Energietransitie.* Groningen: Hanze hogeschool Groningen.

Baarda. (2014). *Dit is onderzoek!* Amsterdam: Noordhoff Uitgeverij.

Basisboek kwalitatief onderzoek, B. e. (2009). *Basisboek kwalitatief onderzoek.* groningen: Noordhoff uitgevers.

Ben Baarda. (2012). *Basisboek methoden en technieken.* Amsterdam: Noordhoff uitgevers.

Ben Riemersma Et Al. (2019). *Historical developments in Dutch gas systems: Unravelling safety concerns in gas provision.* Delft: TU Delft .

Bloomberg. (2010-2018). *Daily year-ahead forward prices of natural gas, CO2 and electricity .* Bloomberg .

C.S. Marchi Et Al. (2017). *Technical References on Hydrogen Compatability of materials, plain carbon Ferritic Steels.* Livermore: Sandia national laboratories.

Chamousis, R. (2016). *Hydrogen: fuel of the future.* Calafornia: The Scientific Research Society.

Christos M. Kalamaras et al. (2013). *Hydrogen Production Technologies: Current State and future developments.* Creative comons attribution licence.

Code of ethics. (2018). *Code of ethics for research in the social and behavioural sciences involving human participants.* Amsterdam: Dean of social science.

D. Hulshof Et Al. (2016). *Market fundamentals, competition and natural-gas prices.* Energy policy.

D.H. Hering. (2010). *Hydrogen embrittlement .* Elmhurst: The Heat Treat Doctor.

Delft, T. (2018). *Net van de toekomst.* Delft: Technische universiteit Delft.

E. Baur Et Al. (2016). *Chemical Resistance of Commodity Thermoplastics.* München : Plastic Design Libary .

E. Shasi Menon, E. A. (2011). *Pipeline Planning and Construction Field Manual.* Sciencedirect .

Enpuls. (2018). *Technologiebeoordeling van groene waterstof productie.* Groningen: TNO.

Erik Polman et al. (2018). *Toekomstbestendige gasdistributienetten.* apeldoorn: KIWA.

F. Tabki Et Al. (2008). *A Mahematical framework for modelling and avaluating natural gas pipeline networks under hydrogen injection.* Toulouse : Elsevier.

Gasontvangststations. (2018, Feb 04). *www.gasunie.nl/begrippenlijst/gasontvangstation*. Retrieved Jun 06, 2020, from www.gasunie.nl: https://www.gasunie.nl/begrippenlijst/gasontvangstation

Gasunie. (2020, may 20). Transformation of the natural gas network . (J. Arends, Interviewer)

Gasunie Et Al. (2018, Feb 03). *Gasunie.nl/begrippenlijst/mengstation*. Retrieved Juni 04, 2020, from Gasunie.nl: https://www.gasunie.nl/begrippenlijst/mengstation

Gasunie hoofdgasnet. (2014). *Gegevens hoofdgasnet en veiligheidsprocedures .* Groningen: Gasunie.

Gasunie Hydrogen. (2020, may 05). Transformation of the natural gas network. (J. Arends, Interviewer)

Gasunie Tennet Et Al. (2020). *Infrastructure Outlook 2050.* Amsterdam: Tennet.

Gaswet. (2000). *article 8 .* The hague: ministry of economic affairs.

Gedragwetenschappen, N. f.-e. (2018). *richtlijn archivering wetenschappelijk onderzoek.* amsterdam: Nederlandse faculteiten maatschappij- en gedragswetenschappen.

gegevensbescherming, A. v. (2018). *Wet AVG.* Den haag: Nederlandse overheid.

GTS. (2017). *Kwaliteit- en Capaciteitsdocument 2017.* Groningen : Gasunie transport services.

H.Iskov Et Al. (2017). *Using the natural gas network for transporting hydrogen - Ten years of experience.* Rio de Janeiro : International Gas Union.

Hen Dotan Et Al. (2019). *Decoupled hydrogen and oxygen evolution by a two-step electrochemical-chamical cycle for efficient overall water splitting.* Israel: Nature energy.

Hydrogen Europe. (2019, Feb 05). *www.hydrogeneurope.eu/Projects*. Retrieved June 1, 2020, from www.hydrogeneurope.eu: https://hydrogeneurope.eu/projects

IEA. (2019). *The Future of Hydrogen.* Japan : International Energy Agency .

IEAGHG. (2017). *Techno-Economic Evaluation of SMR based Standalone Hydrogen Production Plant with CSS.* IE Greenhous Gas R&D Programme.

International Energy Agency. (2015). *Technology Roadmap Hydrogen an Fuel Cells.* IEA.

IRENA. (2018). *Hydrogen: A renewable energy perspective.* tokyo: international renewable energy agency.

John W Creswell et al. (2003). *Research design: Qualitative, quantitative, and mixed methods approaches .* ed: Sage .

KIWA. (2018). *Toekomstbestendige gasdistributienetten.* Amsterdam: Netbeheer Nederland.

L. Lakatos Et Al. (2011). *Advantages and Disadvantages of Solar Energy and Wind-Power Utilization.* Hungary: The Journal of New Paradigm Reseach.

Liander. (2019, maart 10). 'Overbelasting van het elektriciteitsnet neemt toe'. *Duurzaam bedrijfsleven*.

M. Kippers Et Al. (2012). *Waterstof in aardgas op Ameland.* Apeldoorn : Kiwa Gas Technology.

M. Melaina Et Al. (2013). *Blending Hydrogen into Natural Gas Pipeline Networks: A review of Key issues.* Denver: National Renewable Energy Laboratory .

Machiel Mulder Et Al. (2019). *Outlook for a Dutch Hydrogen Market.* Groningen: Centre for Energy Economics Research.

Marcel weeda Et Al. (2020). *Waterstof als optie voor een klimaatneutrale warmte voorziening in bestaande bouw.* Amsterdam: TNO.

Ministery of Economic Affairs. (2017). *Verkenning waterstofinfrastructuur.* Groningen: DNV GL.

Ministery of Economic Affairs and Climate Policy. (2019). *Consultatieversie Integraal Nationaal Energie- en Klimaatplan 2021-2030.* Nederland: Staatsblad.

Ministery of Economic Affairs Et Al. (2019). *Klimaatplan.* Den Haag: Nederlandse staat.

Moosmann et al. (2019). *International Climate Negotations: Issues at stake in view of the COP25 UN.* Luxembourg: Department of Economic, Scientific and Quality of Life Policies.

Mulder, P. d. (2019, Maart 19). Groene waterstof voorlopig veel te duur. (A.D, Interviewer)

NATURALY. (2010). *Preparing for the hydrogen economy by using the existing natural gas system as a catalyst.* Europe : European Union .

Nederland Netbeheer. (2019). *Basisinformation over energie-infrastructuur.* Eindhoven: Netbeheer Nederland.

Network Configuration GTS. (2014). *Ontwerp uitgangspunten transportsysteem.* Groningen: gasunie.

NSWPH. (2018, Feb 12). *northseawindpowerhub.eu/project/*. Retrieved June 10, 2020, from northseawindpowerhub.eu: https://northseawindpowerhub.eu/project/

P. Mancarella Et AL. (2016). *Moddeling of integrated multi-energy systems; Drivers requirements, and opportunities.* Genoa: Power Systems Computation Conference.

Piet verschuren et al. (2010). *Designing a Research Project .* The Hague: Eleven International publishing.

Raad voor leefomgeving en infrastructuur, W. a. (2018). *CO2-arme warmte in de gebouwde omgeving.* Den Helder: RLI.

Regionale Netbeheerders gas. (2003). *Kwaleitsregulering Gasdistributie.* Den Haag: Gasdistributie Nederland.

S. Kneck Et Al. (2017). *Using the natrual gas network for transporting hydrogen - Ten years of experience.* Rio de Janeiro: International Gas Union.

S.D. Paul Et Al. (2013). *Conversion of the UK gas system to transport hydrogen.* UK: Hydrogen Energy Vol 38 .

S.F. van Gessel Et Al. (2018). *Ondergrondse opslag in Nederland - Technische verkenning.* Utrecht : Ministerie van economische zaken en klimaat.

Sebastiaan Hers et al. (2018). *Waterstofroutes nederland.* Delft: TU Delft.

Services, G. T. (2014). *ontwerp uitgangspunten transportsysteem .* Groningen: Gasunie transport services B.V. .

Services, G. T. (2019). *Jaarrekening.* Groningen: GTS.

Stedin Et Al. (2019). *Van aardgas naar waterstof.* Rotterdam & Apeldoorn : Stedin netbeheerd & Kiwa Technology B.V.

Thanh Hua Et Al. (2010). *Technical Assesment of Compressed Hydrogen Storage Tank Systems for Automotive Applications.* Illinois: Argonne National Laboratory.

TNO Energievisie 2030. (2019). *Versneld naar een duurzame energievoorziening.* Amsterdam: TNO.

Verhoeven, N. (2011). *Wat is onderzoek?* Den Haag: Boom Lemma uitgevers.

W.l. Jolly. (2017). *Hydrogen Encylopeadia Britannica .* UK: Britannica.

Wijk, P. A. (2017). *De groene waterstof economie in Noord-Nederland.* Groninge: Noordelijk innovation board.

Appendices

Appendix 1 : Overview of interviews

Company	Date
Gasunie	20-05-2020
Gasunie	01-06-2020
Gasterra	25-07-2020
KIWA	15-06-2020
University of Groningen	/

Appendix 2: Interview Questions (Dutch)

Algemeen

- o Wat voor een functie heeft u binnen de (Company name)?
- o Wat is uw kijk of het feit dat de regering heeft besloten om binnen Nederland minder aardgas te gaan gebruiken voor de laag temperatuur verwarming in woningen en de industrie?
- o Hoeveel impact heeft het klimaat akkoord op jullie branche?
- o Hoe gaan jullie om met de wetgeving die door de overheid is vastgelegd in het klimaatplan?

Aardgas netwerk

- o Wat is de kwaliteitsstandaard van het aardgas netwerk en hoe wordt dit gewaarborgd?
  - Verschil Hoge druk netwerk en lage druk netwerk
- o Wie is er verantwoordelijk voor de kwaliteit van het netwerk?
- o Wat is de levensduur van het aardgasnetwerk binnen Nederland?
  - zit er verschil tussen het hoge druk netwerk en lage druk netwerk?
- o In hoeverre mate is het aardgas netwerk geschikt voor alternatieve gassen zoals biogas en waterstof?
  - Veiligheid
  - Techniek
  - Capaciteit
- o Welke rol kan het aardgas netwerk spelen in het energie systeem van Nederland in de toekomst?

Waterstof

- o Zijn jullie binnen (Company name) bezig met waterstof als energiedrager?
- o Wat voor een kennis heeft u op het gebied van waterstof distributie?
- o Wat voor een rol denkt u dat waterstof in de toekomst kan hebben op het gebied van energie?
- o Wat zijn de nadelen en voordelen van waterstof als dit wordt toegepast als alternatief voor aardgas?

Waterstof netwerk Nederland

- o Is het haalbaar om het aardgasnetwerk te transformeren naar een waterstof netwerk?
- o Welke financiële investeringen zijn er met de transformatie gebonden?
- o Wat is de impact op de CO2 uitstoot als de woningvoorraad wordt verwarmt met waterstof?
- o Heeft het aardgas netwerk dat wordt getransformeerd in een waterstof netwerk genoeg capaciteit om minimaal de woningvoorraad van warmte te voorzien?

Appendix 3: Production Methods Hydrogen

In electrolysis, water is converted into hydrogen and oxygen; electrical energy initiates this process. In its purest form, DC voltage is applied to two electrodes, a cathode, and an anode, which is separated by an electrolyte. Hydrogen is formed at the cathode during this process and oxygen at the anode. There are several variations within electrolysis with Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM) and Solid Oxide Electrolysis (SOE) being the most developed and most common (Enpuls, 2018).

Alkaline Electolyse,

A liquid electrolyte is used during AE, which consists of a mix of water and Potassium and hydroxide. The mix is corrosive. The water is split at the cathode in the liquid electrolyte into hydrogen and hydroxide ions (Hen Dotan Et Al, 2019). The hydroxide ions pass through a membrane where they are oxidized at the anode to O2 and H2O. The operating temperature is between 70 and 90 degrees Celsius, whereby the outlet pressure of hydrogen is usually atmospheric. The hydrogen purity is lower during this electrolysis process, but this is still sufficient for most applications, such as fuel cells. AE is currently the most advanced technology and has played a role in the chemical industry since the last century. The capacities can vary between a few kW to 2.5 MW. Developments are underway where larger cells and production capacity can be generated (Enpuls, 2018). A distinction must be made between the electrolyzer cell's power and the total installation. A total installation can consist of multiple cells and is scaled up by placing multiple cells. Hydrogen production sites of more than 140 MW have been built in this way. Above 2.5 MW, upscaling is realized by multiple cells. Where other equipment can be scaled up and thereby generate an option to economies of scale (Enpuls, 2018).

Proton Exchange Membrane

With PEM, there is no liquid electrolyte but a polymer membrane through which only hydrogen ions can pass. Water is split at the anode into oxygen, hydrogen ions and two electrons. The hydrogen ions and the electrons pass through a polymer membrane where hydrogen is formed in the cathode. The operating temperature is between 60 and 80 degrees Celsius, with an output pressure of 30 bar for hydrogen. In recent years, PEM has developed, resulting in this technology having established itself on the market as a promising technique. PEM is currently widely used for local hydrogen production. The capacities of PEM vary between a few kWs and 2MW. Tests are being conducted with 3 MW cells, and it is expected to scale up to 5 MW in the coming years. Just like AE, larger-scale sizes are realized by placing multiple cells (Hen Dotan Et Al, 2019).

Solid Oxide Electrolyse

SOE uses a membrane made of ceramic material where the water at the cathode is split into hydrogen and oxygen. After this, the oxygen ions pass through a membrane to close the circuit and react with oxygen at the anode. The operating temperature is high, between 700 and 900 degrees Celsius. When external temperature sources can be used, it is possible to achieve high efficiencies. SOE has a lower TRL level compared to PEM and AE. SOE technology has not yet been widely commercialized, and the typical production capacities currently available are between hundreds of kw's (Christos M. Kalamaras et al, 2013). The maximum reported hydrogen production is 740 KW using this technology. However, systems have been developed and demonstrate on a laboratory scale, and individual companies are currently marketing this technology. Figure 9 is a simplified representation of the three different electrolysis technologies.

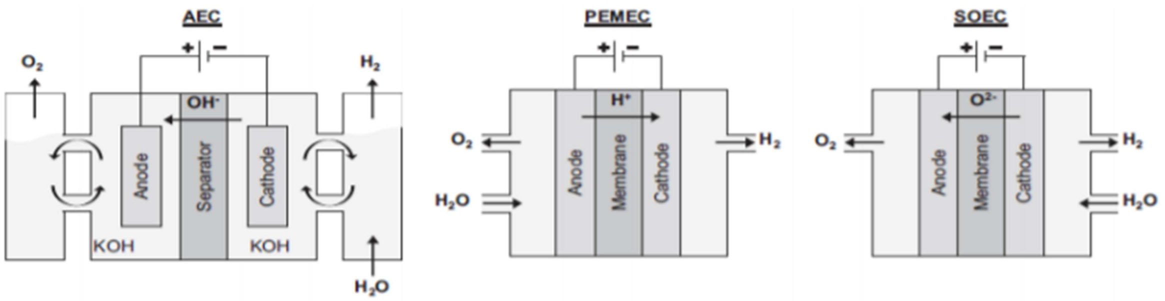

Figure 3: Hydrogen Production Electrolyse scheme **(Hen Dotan Et Al, 2019)**

Production Method SMR

Hydrogen is widely produced through the reforming of natural gas. In industry, reforming reactions are usually carried out in a heated oven over a nickel catalyst. Natural gas is first desulphurized and transported to the steam reformer after adding steam. The steam reformer produces syngas consisting of carbon monoxide (CO) and hydrogen (H2). This syngas is sent to a hydrogen gas shift reactor to maximize the hydrogen yield. The pure hydrogen is the last to be produced in the Pressure swing adsorption installation (PSA). The waste gases from the PSA are burned. The residual heat is used to generate steam in order to reduce fuel consumption. SMR has an average efficiency of 72% with the hydrogen being 99.5 to 99.999% pure (Enpuls, 2018). Figure 10 shows this process schematically. Today, formers are built with a capacity of up to 300,000Nm3 / h hydrogen. Average capacity of a standard factory is 100,000 Nm3 / H hydrogen (IEAGHG, 2017). In addition to hydrogen, a large amount of concentrated carbon dioxide (CO2) is produced, suitable for capture and storage, also known as Carbon Capture Storage (CCS). SMR is not sustainable by nature because clean, renewable energy is not used. Renewable energy can be solved by using biogas instead of natural gas. Hereby the problem of CO2 emissions is still an issue. Hydrogen can be produced onsite utilizing small steam methane reformer installations with average capacities of approximately 150 Nm3 hydrogen per hour. Installations that use biogas and the average size are 150Nm3 per hour, which corresponds to approximately 2 MW of Biogas. Current onsite SMR installations are not suitable for biogas due to the high CO2 content in biogas (IEA, 2019).

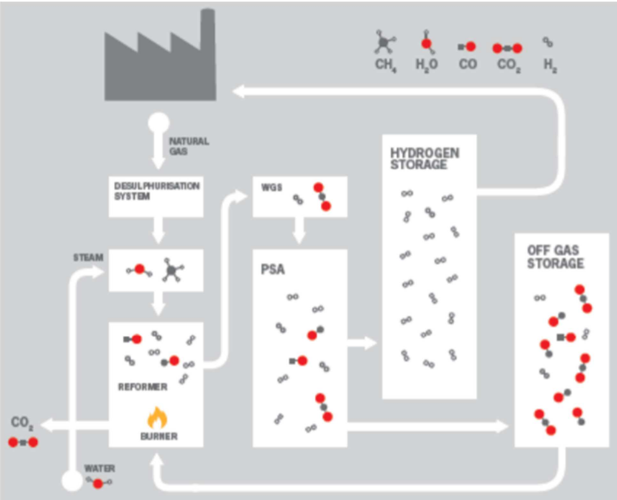

Figure 4: schematic flowchart of hydrogen production due SMR **(Christos M. Kalamaras et al, 2013)**

Appendix 4: Schematic Research Framework

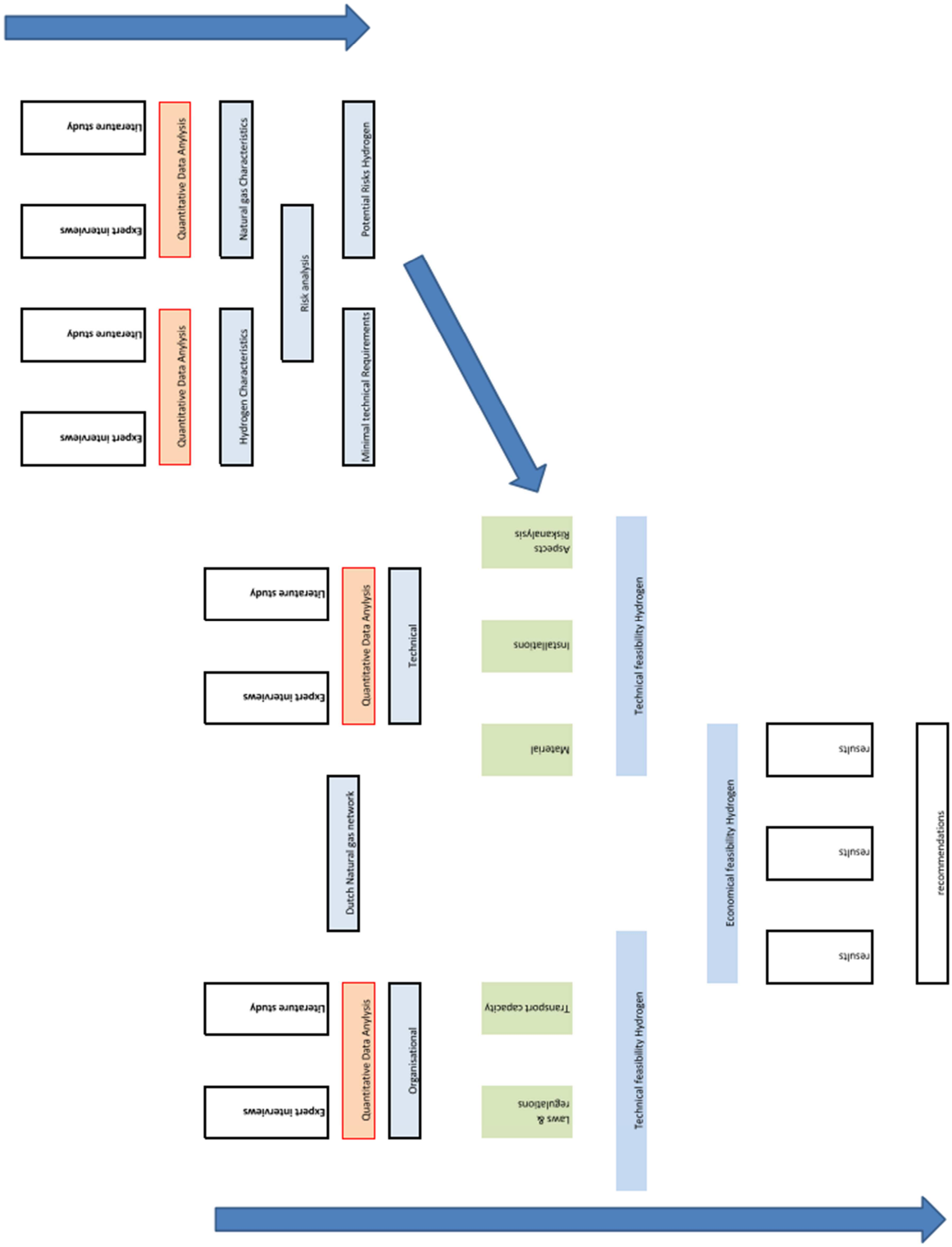

Figure 5: Schematic Research Framework