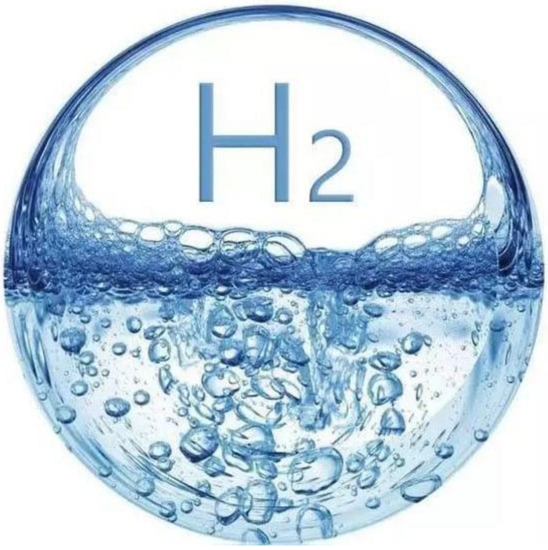

UTRECHT UNIVERSITY
Graduation Research

Fleur de Haan
25-07-2019

CONVERSION OF THE GAS NETWORK OF GRONINGEN INTO AN ALL-ELECTRIC AND HYDROGEN CONFIGURATION TO MEET HOUSEHOLDS ENERGY DEMAND

Based on the 3 renewable energy scenarios developed by Netbeheer Nederland

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Abstract

In the Netherlands 82% of the households are connected to the gas network. Consequently, 42% of the direct energy use of a household is provided by natural gas which translates into 39% of the total CO_2 emissions of a household. In line with the climate goals the Dutch government has proposed that in 2050 no household will use natural gas anymore. Hydrogen is proposed as a substitute since it can be distributed in the current gas network, it can be produced by a low-carbon route and it can be stored on a large scale.

Converting the complete network to hydrogen would not be energy efficient since green hydrogen needs to be produced by electrolyzing water with the use of electricity. This electricity could also be used directly in households. A mix of hydrogen and electricity makes sure that there is a higher energy efficiency due to electrification and that the intermittency of renewable electricity production can be dealt with by means of hydrogen storage.

Three renewable energy scenarios, local, national and international, for the Netherlands are used as input to calculate the hydrogen demand for Groningen in 2050. To use (part of) the current gas assets to distribute hydrogen, the network was divided into gas clusters based on the main distribution pipelines. These clusters are by means of a multi-criteria analysis ranked on the best options for either hydrogen or all-electric based on five parameters which are related to the supply area, the energy label, the type of building, monuments and possible congestion of the electricity network.

Based on the hydrogen demand per scenario, the gas distribution potential, and the ranking, three configurations of the network were developed. Since the local scenario is mainly based on a self-sufficient and decentralised approach this is not in line with a more centralised conversion of the gas network. Therefore, it is expected that the network would more likely evolve like the national or international scenario. In these scenarios between 35 and 40% of the gas assets will be converted to hydrogen. This implies that a big portion of the gas assets will be depreciated, and that the electricity infrastructure needs a significant investment.

Further research is needed to show how the clusters can be converted over time, the resulting costs and the different roles of the stakeholders in such an extensive project.

Key concepts:
Hydrogen, all-electric, energy scenarios, natural gas infrastructure, households, Groningen

Preface

This graduation research has been carried out for Utrecht University and Accenture Consulting (Resources operating group). This graduate research was conducted from March 2019 until August 2019 as part of the Master Program Energy Science and an internship at Accenture.

The research topic gained my interest since lately there has been a lot of interest from several parties regarding the use of hydrogen as an energy carrier in the current infrastructure as a substitute for natural gas. Often it is proposed as being the silver bullet to decarbonise the built environment, but no concrete projects had evolved yet and I soon realised that, as with everything, also using hydrogen has advantages and disadvantages. By combining hydrogen and electricity these energy carriers could potentially complement each other. To aid in the energy transition I made a first attempt to develop a concrete proposal of how the built environment for Groningen could evolve with the inclusion of hydrogen as an energy carrier.

I hope that you will both enjoy reading this research and get some more insights. If you're not a fan of reading, an infographic can be found in appendix A.

If there are any additional questions, feel free to contact me.

Fleur de Haan
25 July 2019

Acknowledgement

I would like to thank several people for their support and contribution regarding this graduation research. First, I would like to thank Gert Jan Kramer, my supervisor from Utrecht University for the discussions we've had regarding this topic. Secondly, I would like to thank Guido Houben and Jessica Pfeiffer my supervisors at Accenture. They've showed great interest in the topic, provided critical feedback and guidance regarding the developments of the research, and helped me find my way at Accenture. Furthermore, I would like to thank everyone within Accenture I've (informally) spoken to about the topic and who have helped me figure out the software program ArcGIS Pro.

Contents

List of abbreviations

Abbreviation	
CBS	Centraal Bureau voor de Statistiek
CCS	Carbon Capture and Storage
COP	Coefficient Of Performance
CO_2	Carbon dioxide
DSO	Distribution System Operator
ETS	Emission Trading System
GHG	Greenhouse Gas
GIS	Geographic Information System
MCA	Multi-criteria Analysis
NTP	Normal Temperature and Pressure
TSO	Transmission System Operator

1. Introduction

1.1 Societal background

To be able to prevent dangerous anthropogenic climate change, the level of greenhouse gas (GHG) emissions should be consistent with the goal of staying below 2.0 °C global mean temperature change, and preferably even below 1.5 °C. The global energy system requires a fundamental transformation moving towards higher energy efficiencies, low-carbon energy supply technologies, renewable energy sources and carbon dioxide capture and storage (Bruckner, 2016). In 2015, for the first time, 195 nations were brought together and were able to reach an agreement to mitigate climate change and adapt to its effects. In the Paris Agreement each government presented an implementation plan to reduce the emissions within their borders to contribute to reaching this collective goal (UNFCCC, 2015).

For the Netherlands, to achieve the 2.0 °C target, this translates into a CO_2 reduction of around 90% to 100% by 2050 (compared to 1990) and to reach the 1.5 °C target this would require more than a 100% reduction by 2050. This corresponds with a CO_2 reduction in 2030 of around 40% to 50%. In practice, the CO_2 emissions are decreasing gradually and at the current rate only a reduction of 20% would be reached in 2030 (van Vuuren, Boot, Ros, Hof, & den Elzen, 2017). So, far-reaching and unprecedented changes are required in all aspects of society to reach the climate goals in 2050 (Stocker et al., 2018).

One of the areas that contributes significantly to the emission levels in the Netherlands is the use of natural gas in households since 82% of the households are connected to the gas network. Consequently, 42% of the direct energy use of a household is provided by natural gas used for cooking, and heating of rooms and water which translates into 39% of the total CO_2 emissions of a household (Gerdes, J.; Marbus, S.; Boelhouwer, 2016). In addition, an ever-increasing number and severity of earthquakes in the province of Groningen due to natural gas extraction decreases the public acceptance of extracting natural gas (van der Voort & Vanclay, 2015). That is why the Dutch government has proposed in the energy policy that in 2050 no household will use natural gas anymore (Ministry of Economic Affairs and Climate Policy, 2016).

1.2 Scientific background

There are some possible alternatives to using natural gas in households, like moving to an all-electric society, using district heating or using biomethane or hydrogen gas. Each of these options have advantages and disadvantages and there is not one silver bullet. A district heating system consists of a system of insulated pipes that transport heat that is generated in a centralized location for residential or commercial heating requirements like space- and water heating. The sustainability of district heating depends on the heat source, which could be (waste) heat from, the industry, from coal-fired power plants, and natural gas plants (Afman & Rooijers, 2017). Thereby, the source should preferably be situated close to areas with a high energy demand to minimise energy losses due to distribution (Persson & Werner, 2011).

The main advantage of electrification is that, with the use of a heat pump, a high energy efficiency can be realised that is denoted by the coefficient of performance (COP). The COP is the ratio between the energy usage of the compressor and the amount of useful heat extracted from the condenser and is often a value between 3 and 5. A high COP value represents a high efficiency. In comparison, the energy efficiency of converting electricity into hydrogen and using this hydrogen in a gas boiler is only 62% compared to an overall efficiency of 230-410% for a heat pump as can be seen in Figure 1 (Goater et al., 2018). Unfortunately, for electricity, large scale storage to meet peak demand and seasonal fluctuations is not yet available in the Netherlands, mainly since the landscape limits the applicability of pumped hydroelectric storage (Evans, Strezov, & Evans, 2012).

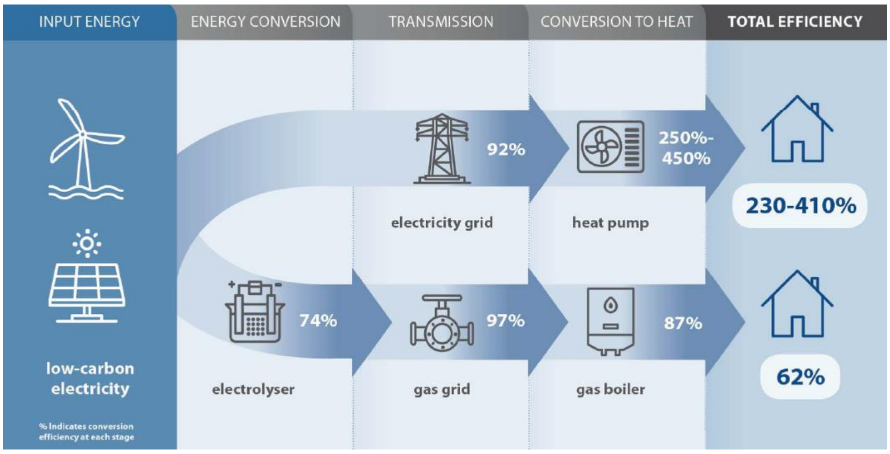


Figure 1. Relative efficiency of heating: electricity in heat pumps vs. hydrogen in boilers (Goater et al., 2018)

Hydrogen as an energy carrier has the advantage that it can be produced by a low-carbon route and that it can be stored on a large scale to meet peak demand. Other than that, it's a renewable source of energy that can be produced in several ways. Currently, most hydrogen is still produced from fossil fuels, but in the future this could shift to either using electricity produced by renewable sources to electrolyze water and produce hydrogen or to use natural gas in combination with carbon capture and storage (CCS) as planned in Norway and the United Kingdom (Goater et al., 2018)(Sadler, D., Cargill, A., Crowther, M., Rennie, A., Watt, J., Burton, S., Haines, M., Trapps, J., Hand, M., Pomroy, R., Haggerty, K., Summerfield, I., & Evans, 2016). Finally, hydrogen can add more flexibility to the energy system since it has a broad applicability and it can connect various markets such as industry, mobility and the built environment (Gigler & Weeda, 2018).

Since 82% of the households in the Netherlands are connected to the gas network there is already an extensive network available that could potentially lose its value when natural gas would be put aside (Gerdes, J.; Marbus, S.; Boelhouwer, 2016). For transmission system operators (TSOs) and distribution system operators (DSOs) hydrogen could become a substitute. So, even though the production and use of hydrogen is less efficient than electrification, it can readily be stored at a large scale and can become a low-carbon replacement for natural gas when full electrification is not a suitable option and to add flexibility to the system (Goater et al., 2018).

Not surprisingly, hydrogen is gaining more and more attention. In the Dutch Energy Agenda, hydrogen is one of the pillars of the energy transition (Ministry of Economic Affairs and Climate Policy, 2016). In addition, in the Netherlands there are currently over 100 hydrogen initiatives, in various stages of development, and this number is constantly growing. These are small-scale initiatives and in order to initiate a system change, strong long-term commitment is required on the part of the business community, the industry and the government with contributions from knowledge institutions and social organisations (Gigler & Weeda, 2018).

1.3 Problem statement

Not only the way in which the energy will be distributed in the future is still insecure, also the way in which the energy will be generated is still in the transition phase. The distribution network will need to adapt to this since the daily and seasonal intermittency of the different sources will require a certain amount of flexibility including storage possibilities. A more international orientated network might lower the storage capacity needed since the under- and oversupply of electricity can be imported or exported when needed. Netbeheer Nederland has developed 3 societal 2050 scenarios to determine how the energy demand for power and light, low temperature heat, industry and transport can be met by renewable sources (Afman & Rooijers, 2017) (Hermkens et al., 2018).

Based on these scenarios, TSOs Gasunie and Tennet have studied and modelled how, per scenario, this can quantitatively evolve (Gasunie & Tennet, 2019). Since studies, like the ones commissioned by the Ministry of Economic affairs and the branch organisation for electricity and gas network operators, have already shown that converting the gas network into a hydrogen network is technically possible, hydrogen also plays a significant role in these scenarios (van der Noort, Vos, & Sloterdijk, 2017) (Hermkens et al., 2018). However, for this transition to become concrete, research is required that shows how an all-electric and hydrogen network can develop in practice (Gigler & Weeda, 2018) (Gasunie & Tennet, 2019).

Several municipalities have already conducted a study in which per neighbourhood the best energy solution for households is determined when natural gas would no longer be an option. In most of these studies using hydrogen in the existing network is not considered and thus the existing gas pipeline assets are neglected or when hydrogen is considered the existing pipeline network does not form an integral part of the assessment (Municipality of Amsterdam, 2016) (Noorma, K. Noordenburg, 2016). A study that integrates the assets by clustering the gas pipelines in a way that the existing pipeline network can be used efficiently would add to the existing knowledge base and can show the relevance of taking this into account.

Groningen could prove to be a suitable area for a case study since there is a strong social push to move away from natural gas which increases the willingness of the residents to aid in the conversion process. In addition, it's a key location in the Dutch gas- and electricity infrastructure, including that it's close to potential hydrogen storage locations. Lastly, in this area some of the buildings are relatively old and consequently have a significant heat demand. Developing a suitable energy system for households will show that it's possible and will aid the energy transition (Collective of companies, 2019).

1.4 Research question(s)

How can the existing gas network of Groningen be clustered and based on these clusters what are suitable hydrogen and all-electric configurations to meet the household's energy demand in 2050?
Based on the 3 renewable energy scenarios developed by Netbeheer Nederland
a). How can the area be divided into suitable clusters based on the characteristics of the existing gas network and what is the gas distribution potential per cluster?
b). What are the parameters that define the suitability of a cluster for conversion into hydrogen or all-electric and how can they be quantified, classified and weighed?
c). What are the network configurations in 2050, based on the gas distribution potential, result per cluster and the specifications of every scenario?

1.5 Research objective

Apart from using and combining the existing literature to add to the knowledge base, the method that is used to convert Groningen into a hydrogen and all-electric configuration can be used for all the different regions in the Netherlands. The objective was to develop a framework that can be used for cities or areas in the Netherlands to find a proper way of converting gas clusters into all-electric and hydrogen areas considering the energy scenarios of Netbeheer Nederland for 2050.

2. Theoretical background

In the theoretical background the scenarios are first explained since they form the input for the data used in this research. Then there is a general section about hydrogen and a section that explains the differences between using natural gas or hydrogen in the network. Followed by a general section about an all-electric set-up. In the last part the key differences between hydrogen and all-electric are elaborated on. The theoretical background is used mainly as input to find the parameters that influence whether an area is suitable for either hydrogen or all-electric.

2.1 Scenarios

Since this study is done for 2050, the future energy demand of the households is unknown since it will be affected by things such as population growth, energy efficiency improvements and regulations. To deal with this uncertainty, different future scenarios were studied. CE Delft, an independent research consultant, has developed four energy scenarios for 2050. This study is commissioned by Netbeheer Nederland, the Dutch collective of grid operators (Afman & Rooijers, 2017). These scenarios are chosen since they are perceived as being state-of-the art scenarios and are widely used in the literature. Thereby, the study is conducted and commissioned by independent parties.

The aim of the study was to develop different possible scenarios for a CO_2 neutral society in 2050 based on different social and political inputs. The scenarios differ regarding who will oversee the transition, at which level it will be steered and to what extend self-sufficiency will be realised. For the calculations described in the method only the regional, national and international scenarios are considered due to data limitations for the generic scenario.

Regional

In the regional scenario the provinces and municipalities will be in control, citizens take initiative and play an active role. Most of the energy to produce electricity and heat will be derived from local energy sources such as sun, wind, biomass and geothermal energy. To tackle the temporal and spatial mismatch between the local energy sources there is a far greater need for a new energy infrastructure and hydrogen storage. The municipalities will be self-sufficient which implies that the energy will be produced and converted decentral.

National

The central government is in control and an energy-autonomy for the Netherlands will be realised by mostly central sources of energy like off-shore wind. The central government initiates large projects regarding off-shore wind, energy-islands in the North-Sea and at central locations where (part of the) electricity can be converted to gaseous energy carriers. To cope with the temporal mismatch between supply and demand there is a substantial need for these gaseous energy carriers. The conversion of electricity to hydrogen will take place close to the coast or even offshore.

International

The government supports international energy trade and the Netherlands will be one of the players in a broader energy context. It will import several forms of renewable energy, including biomass, and there is an international production and trade of hydrogen derived from climate-neutral sources (renewable and fossil with CCS). In addition, other energy carriers are considered like ammonia and renewable hydrocarbons. This extensive availability of CO_2-neutral energy carriers translates into different energy solutions.

Generic

This scenario is based on an organic process steered by a strong CO_2 price-signal but without governmental intervention. This will be either done by putting a price on GHG emissions in the form of a tax or by implementing an emission trading system (ETS) which issues a certain number of permits that can be traded against a market-based price. Since there is no central steering the energy mix will consist of local and international energy sources. Large-scale project that require coordination and upfront investments will not be realised (Afman & Rooijers, 2017).

2.2 Hydrogen

Production

Hydrogen is the most abundant and simple element of the universe but as a gas it is not readily available in nature since it is usually found bonded with oxygen or carbon. There are several production methods available, it can be produced from conventional sources by steam reforming of natural gas, partial oxidation of hydrocarbons and coal gasification. Currently 96% of the hydrogen is produced from hydrocarbon sources like natural gas, oil and coal by steam reforming (Wang, Wang, Gong, & Guo, 2014). Since these processes are not sustainable or renewable this type of hydrogen is called grey hydrogen, when the processes are combined with carbon capture and storage (CCS) the hydrogen is called blue hydrogen. Green hydrogen is produced by using electricity produced by renewable energy sources to electrolyze water into hydrogen and oxygen by electrolysis (Kothari, Buddhi, & Sawhney, 2008). Considering the climate goals, in 2050 (part of) the electricity surplus originated by the intermittency of renewable sources would be used to electrolyse water. Since it's expected that this would be the main production route in 2050 it is explained in further detail.

Electrolysis of water

Electrolysis is the process in which an electric current is passed through a substance to induce a chemical change. Electrolysing water is done by means of inducing a redox reaction. A redox reaction is a type of chemical reaction that involves the transfer of electrons between two molecules, atoms or ions. A redox reaction consists of a reduction and an oxidation reaction, that always occur together. Since at ambient temperature and pressure this reaction is not favourable in thermodynamic terms, excess energy in the form of electricity is required to induce the redox reaction in pure water. For water the following reactions will occur;

At the negatively charged cathode, a reduction reaction takes place, with electrons (e^-) from the cathode being transferred to hydrogen cations to form hydrogen gas. The half reaction is:

$$2\, H^+(l) + 2e^- \rightarrow H_2(g) \qquad (1)$$

At the positively charged anode, an oxidation reaction occurs, generating oxygen gas and transferring electrons to the anode to complete the circuit:

$$2\, H_2O\ (l) \rightarrow O_2(g) + 4H^+(l) + 4e^- \qquad (2)$$

Under optimal conditions this will result in pure hydrogen and oxygen gas (Wang et al., 2014).

2.3 Natural gas versus hydrogen

Chemical characteristics

Like natural gas, hydrogen is tasteless, odourless and colourless so a chemical with an odour will need to be added to hydrogen, as is done with natural gas, when it would be used in households. Compared to natural gas the energy mass content is around 3 times as high, on the other hand, hydrogen has a very low density at ambient conditions which results in a lower energy volume content of hydrogen of 10,7 MJ/m^3 compared to 36,4 MJ/m^3 for natural gas (Mazloomi & Gomes, 2012). This means that to store the same amount of energy at ambient temperature and pressure the storage capacity needs to be three times as large.

Line pack capacity

This lower energy volume content also influences the line pack capacity of the network. The line pack capacity is the volume of gas that is stored in the pipeline network during normal operation, and peak gas demand is currently met by using this line pack capacity as a short-term storage reservoir. When hydrogen is distributed at ambient temperature and pressure in the same network the line pack capacity will significantly decrease. When the same amount of energy needs to be supplied, either additional storage could be required, or the operating pressure should be increased in the pipeline network (Dodds & Demoullin, 2013).

Safety

Hydrogen in comparison to natural gas can lead to hydrogen embrittlement. According to a study done by DNVGL, the largest technical consultant and supervisory to the global renewable energy and oil & gas industry, considering the composition of the Dutch gas network, for the pipelines in the Netherlands this would not lead to a significant difference. In addition, hydrogen can influence the fatigue of steal and consequently the lifespan of the pipelines. When taken care of, it will mainly influence the operational side by switching to polyethylene pipelines, or by replacing the existing pipelines more frequently (van der Noort et al., 2017).

Due to the lower energy density of hydrogen it's expected that the leakage of hydrogen would be higher than of natural gas. Considering it's a flammable gas with a wide flammable limit raises questions regarding the safety of using it in households. However, the stoichiometric mixture, which is the perfect mixture for combustion, is circa 29% on a volumetric basis with air. For natural gas this is 10%, which means that to get the perfect combustion about three times the concentration of hydrogen is needed compared to natural gas. Relating this to the low density and high diffusivity of hydrogen, these volumetric values are difficult to obtain in domestic properties. (Sadler, D., Cargill, A., Crowther, M., Rennie, A., Watt, J., Burton, S., Haines, M., Trapps, J., Hand, M., Pomroy, R., Haggerty, K., Summerfield, I., & Evans, 2016) .

2.4 All-electric

The future energy scenarios all forecast that the electricity supply will increase due to an increase in the production of renewable electricity by, amongst others, wind and solar technologies. With this in mind, heat pumps are widely seen as a key technology to deliver low-carbon heating in households (Fawcett, 2011).

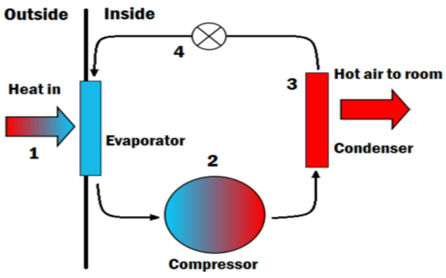
Electricity network

Power transformers and congestion

According to the scenarios of Netbeheer Nederland it is likely that the electricity demand will grow in the future. This growth will have an impact on the electricity network since, to avoid congestion, the network will need to be expanded (Gasunie & Tennet, 2019). Especially in densely populated areas the available room for power transformers and additional high-voltage lines might be limited. According to CE Delft, for some elements, the capacity of the electricity grid will need to increase by a factor 5 and these elements are often found in densely populated areas (Afman & Rooijers, 2017).

Heat pump

Heat pumps make use of the energy of low temperature heat derived from the environment to turn it into higher temperature heat with the use of electricity.



The basic principle is that low temperature heat is absorbed from the environment by a working fluid in the evaporator. With this energy the low-pressure working fluid turns into a vapour which reaches the compressor. With the input of electricity, the vapour is further compressed, thereby increasing the temperature. In the condenser this high-pressure and high-temperature vapour condenses to a liquid while releasing heat to the inside environment. The last step is that the liquid is again transformed into a low-pressure and low-temperature liquid after which the cycle starts again (Fawcett, 2011).

Coefficient of performance

The coefficient of performance (COP) of a heat pump indicates how many units of heat can be delivered for every unit of energy input. The theoretical maximum efficiency of a heat pump is described by the Carnot-efficiency (Blok, 2016).

$$COP_{h,carnot} = \frac{T_{condenser}(K)}{T_{condenser}(K) - T_{evaporator}(K)} \qquad (3)$$

This is an important equation since it shows important key characteristics of heat pumps. The pump will operate most efficiently when the temperature gap between the heat source and heat demand is minimised. Since the heat source depends on the outside temperature and can't be influenced the COP will be higher with a low temperature heat demand. In newly build homes underfloor heating systems typically use heat between 30-35 ºC, compared to the traditional radiator systems that use heat at 60-75 ºC (Fawcett, 2011).

Insulation

For a heat pump to work effectively and to be able to reach the desired temperature the buildings need to have a certain level of insulation. This is mainly since the home is heated with a lower temperature source compared to using a boiler and to still be able to reach the desired temperature, the heat loss through the walls, roof and floor should be minimised (Hepbasli & Kalinci, 2009). For a fully electric heat pump an energy label of at least label B is necessary, for a hybrid heat pump label C is sufficient (Natuur & Milieu, 2016).

Space

A heat pump is a quite large installation with an inside and outside unit that in addition could make quite some noise when in operation. This makes it in general a less suitable option for building types where households have a smaller living area like flats and apartments. In these types of buildings there is both a limited outside and inside space and the living areas in the houses would likely be situated next to the heat pump installation. In addition, to be able to distribute the heat, a pipeline infrastructure is needed which requires additional space in the walls and floors (SEAI, 2019).

2.5 Hydrogen versus all-electric

To give a conclusive answer regarding the conversion of the gas clusters into either hydrogen or all-electric the characteristics and the resulting impacts should be compared. A proper mix will be needed since by only using hydrogen in the gas network there will be significant energy losses since there are losses during electrolysis, transport and in the gas boiler. For the all-electric option, the electricity is transported and directly used by a heat pump which uses outside heat and electricity and consequently has a high efficiency. Unfortunately, storing electricity for a longer period is not so easy, and hydrogen turns out to be a good option to deal with this both intraday and seasonal intermittency of renewable electricity generation. So, both options are needed but depending on the characteristics of the technologies, buildings and gas and electricity infrastructure, a suitable system should be designed.

3. Method

3.1 General outline of the method

The method is divided into three parts that do not need to be carried out in a linear sequence but that are all needed for the final part. The general outline of the method can be found in Figure 2. Horizontally a division has been made between the three parts, for every part the components or steps are shown that lead to the results used to develop the cluster configurations. The vertical division is between whether the result or the data obtained are general for the Netherlands or specific for Groningen. Since most data is found for the Netherlands in general, the data is converted to data applicable for Groningen. Per part the steps will be further explained with between brackets the corresponding step.

In part 1 the renewable energy scenarios described in section 2.1 are studied (scenarios) and used to calculate the household's electricity and hydrogen demand in 2050 for Groningen (hydrogen demand). In part two based on the gas network of the Netherlands (gas network), Groningen is divided into clusters (gas clusters). These clusters are developed to study in part three which ones would be most suitable to convert to hydrogen and, also based on the current assets, what amount of gas the cluster could potentially distribute (gas distribution potential).

Part 3 consists of a multi-criteria analysis. The literature is used to define parameters that impact the suitability of a cluster for either hydrogen or all-electric (parameters). After which these parameters are quantified (quantification) and give a relative weight (weighing) to develop an overall ranking (ranking). In the last step, per scenario, based on the hydrogen demand, gas distribution potential and ranking of the clusters an optimal configuration between hydrogen and all-electric is developed for Groningen.

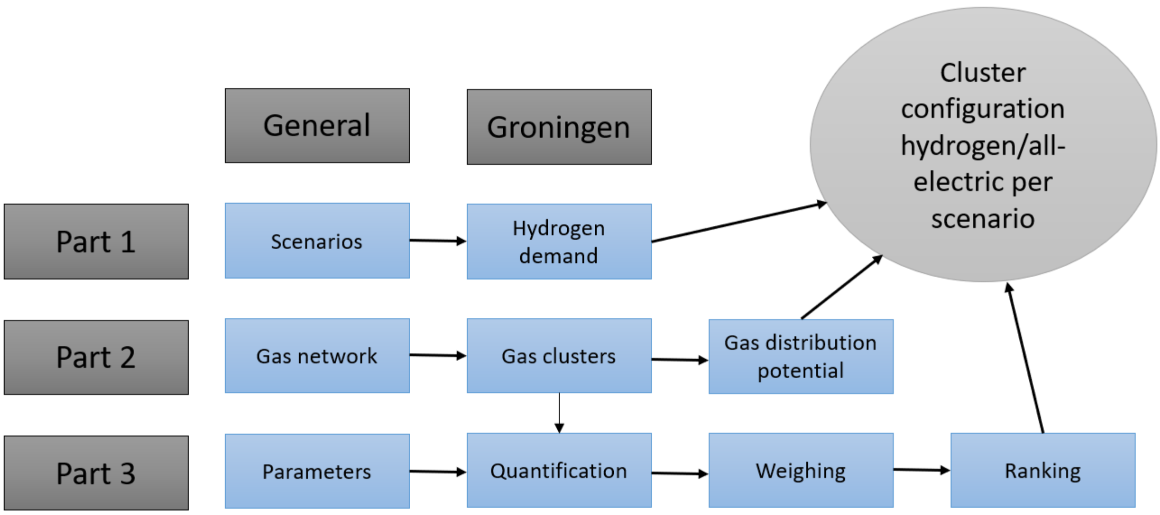


Figure 2. Graphical representation of the method

ArcGIS Pro

In part 2 and 3 ArcGIS Pro is used as the main tool to get the results and will be briefly explained here. Like any geographic information system (GIS), ArcGIS Pro is a tool where you can capture, combine, analyse and present spatial and geographic data (ArcGIS, 2019). GIS software is used when the spatial aspects are an integral or important part of the data which is in line with this study. By using a GIS tool both the geographic information of the clusters and the parameters can be combined.

In part 2 ArcGIS pro is used as the main tool to cluster the gas network based on the spatial data regarding the gas network. The main advantage of using a GIS software in this part, is that it's relatively easy to extract and present only the data that is needed for the analysis. In part 3 ArcGIS Pro was mainly used to combine the geographic data for the clusters with the data for every parameter. For these kinds of analysis several tools of ArcGIS pro are used and will be further elaborate on in each part.

3.2 Part 1: Scenarios Netbeheer Nederland

Based on the energy scenarios the demand for hydrogen in 2050 in terms of the amount of energy it can provide is calculated. This demand is also used as the input to calculate the volumes of hydrogen the gas pipelines need to transport. These values for the Netherlands are converted to values for Groningen based on current demographics and expected trends like urbanization and immigration.

The scenarios developed by CE Delft, commissioned by Netbeheer Nederland, are chosen since these are seen as state-of-the art scenarios and are thus often used in other studies, for instance in the study done by Gasunie and Tennet that focusses on the infrastructure outlook for 2050 (Gasunie & Tennet, 2019). In addition, similar studies conducted by municipalities have used these values, which aids in comparing these studies with the results obtained (Municipality of Amsterdam, 2016) (Noorma, K. Noordenburg, 2016).

Hydrogen

Energy demand

Based on the future energy scenarios developed by Netbeheer Nederland and the follow-up study done by Gasunie and Tennet, per scenario, the demand for hydrogen in 2050 is calculated. In the scenarios the total final demand is given for all the households and specifically what part will be provided by electricity, hydrogen or (bio)methane (Afman & Rooijers, 2017) (Gasunie & Tennet, 2019). The original data for the energy demand for the households in the Netherlands per scenario is shown in Table 19 in appendix B. Since in this study the focus is only on all-electric and hydrogen, the energy that is provided by (bio)methane will be supplied by hydrogen since both (bio)methane and hydrogen are gasses and would require a similar (gas)infrastructure.

Volume

Since the amount of energy that needs to be provided by hydrogen is known the corresponding volume in cubic meters can be calculated. As mentioned before, hydrogen has a lower energy volume ratio under normal temperature and pressure (NTP) which would imply that without any adaptations in the gas network a larger volume of hydrogen needs to be transported to distribute the same amount of energy. However, according to a study done by DNVGL, the largest technical consultant and supervisory to the global renewable energy and oil & gas industry, it is relatively easy to adjust the gas network in such a way that it can transport the same amount of energy with hydrogen as it could with natural gas by mainly increasing the pressure in the pipelines (van der Noort et al., 2017). It will thus be assumed that the same energy content will be distributed by hydrogen.

Since the amount of energy that can be transported by means of hydrogen per cubic meter in the gas network is not known but assumed to be like that of natural gas this volume is first calculated. According to Enexis, the DSO in Groningen, the energy content of natural (Gronings) gas is 35,17 MJ/m^3 (Enexis, 2018). With this value, per scenario, the volume that would be needed to provide the amount of energy by means of distributing natural gas in the scenario's is calculated and consequently also the volume of hydrogen gas.

Groningen

Since the above-mentioned data is for the Netherlands these values need to be converted to the values for Groningen which will be based on demographic data. Converting these values will not be as straightforward as just using a percentage of the future values based on the current demographics, mainly because of an expected increase in immigration and urbanisation (Kooiman, de Jong, Huisman, van Duin, & Stoeldraijer, 2016).

The values in the scenarios are given for 2050 for the Netherlands, so the conversion is based on the number of inhabitants in 2050 in Groningen compared to the number of inhabitants in the Netherlands. Centraal Bureau voor de Statistiek (CBS) and Planbureau voor de Leefomgeving (PBL) estimated that the relative population growth of Groningen will be slightly higher due to urbanization and immigration than the national growth (Kooiman et al., 2016).

The population estimations for Groningen are carried out until 2040 instead of 2050. To be able to extract these until 2050 the percentage of the population living in Groningen compared to the Netherlands is calculated for 2040. There is a small growth estimated from 2040 to 2050 as can be seen from *Figure 3* for the Netherlands. Based on this small growth it's assumed that there will not be a significant difference regarding the percentage of people living in Groningen in 2050 compared to 2040. That's why this percentage is used to, based on the population forecast of the Netherlands in 2050, calculate the population of Groningen in 2050.

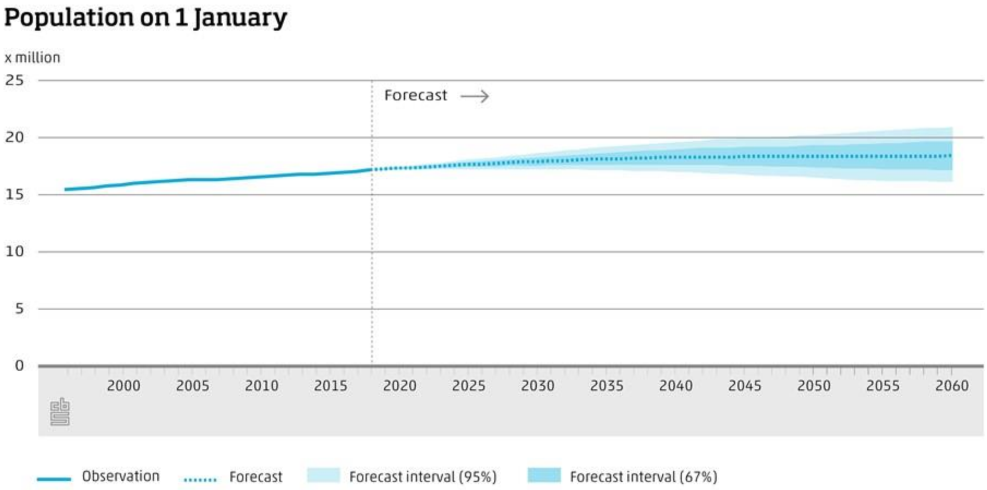


Figure 3 Estimated population size Netherlands (Kooiman et al., 2016)

Energy demand and hydrogen volume Groningen

By combining the hydrogen data for the Netherlands and the population data for Groningen the hydrogen demand is calculated for Groningen. It's assumed that the energy demand is only based on the population size which is not necessarily the case. There could be other factors involved, for instance, in areas that are densely populated people tend to have smaller houses and thus consume less energy, older buildings in general will need more energy, and so on. However, since Groningen is a relatively large part of the sample it's expected that the minorities will even out. Thereby, the data is derived from scenarios for 2050 in the first place which give an expected figure.

3.3 Part 2 Gas network

In part 2 the main pipelines of Groningen are distinguished by adding two constraints, regarding the pressure and the pipeline diameter, to the original data. Based on the main pipelines the area is divided into 8 clusters that cover Groningen. For each of these 8 clusters the gas distribution potential is calculated.

Pipeline data

For Groningen the distribution system operator (DSO) is Enexis. Enexis has all their data regarding their pipelines in a format that can be exported into a GIS. The data regarding the gas pipelines consist of, the pressure, the pipe diameter, the length and other variables. When exported to ArcGIS Pro, the raw data looks like Figure 4 in which all the pipelines are shown. In addition, data from CBS is used to calculate the gas distribution potential after clustering of the area (CBS, 2019).

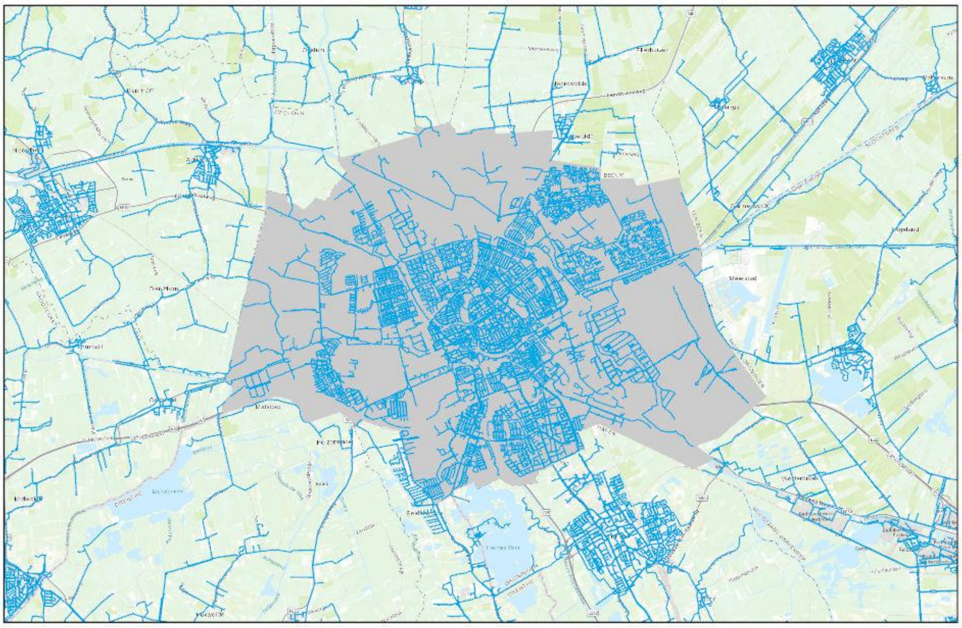


Figure 4 Gas pipeline data Enexis (Enexis, 2019)

Clustering

As can be seen from Figure 4 the gas infrastructure in the Netherlands and in Groningen specifically is an extensive and well-developed network of pipelines that are all in a certain way connected. These clusters are mapped in such a way that with relatively small adjustment a cluster can be disconnected from the other clusters without causing (significant) issues somewhere else in the network. This is done to make use of the existing gas assets instead of having to install even more gas pipelines. In clustering the gas network, the pipe diameters, the pressure, the location of the pipelines and the pipeline density are thus considered.

Pressure

The first step in clustering the gas network is to determine which pipelines have a certain pressure to distinguish the main pipelines used to transport the gas through Groningen. High pressure pipelines are used to transport the gas nationally and even internationally. The distribution system operator receives the gas at a pressure of maximum 8 bar (medium pressure) and distributes this at a regional level. The low-pressure pipelines are pipelines lower than 1 bar and are the pipelines close to the end-user (Enexis, 2014). To only show the main pipelines a constraint is added that will only show the pipelines with a pressure of at least 1 bar and a maximum of 8 bar which are the medium pressure pipelines.

Pipe diameter
In addition to the pressure, a pipeline with a larger diameter can distribute a larger volume of gas. Since the aim is to only show the main gas pipelines the pipe diameter will also be used as a constraint. For the pipe diameter there is not an uniform division between the pipe diameter range for low pressure pipelines and medium pressure pipelines. The pipelines in this data set have a pipe diameter ranging from 15 until 600 mm and by analysing the data it was found that by adding a constraint for 100 or 200 mm only some of the main supply pipelines are left and can be used for clustering.

Location of main supply pipelines
By applying the above constraints, the main medium pressure supply pipelines are shown. Based on these pipelines the area is divided in clusters. These clusters are developed in such a way that in general the boundaries of every cluster follow these main pipelines. The rationale behind this is that since these pipelines are located on the boundary of two clusters, the assets could be used by both, or one of the two clusters. If one of the clusters would become all-electric this would have less consequences for the next clusters since the pipelines can still be used by the other cluster.

Area
The area is divided into 8 clusters, which is mainly done to stay within the scope of the research, since for every additional cluster the area needs to be analysed separate which requires a significant amount of work. With 8 clusters a relevant analysis can be done within the time limits. As noted before these 8 clusters are based on the location of the main supply pipelines but in addition the pipeline density is considered to create clusters with a relatively similar distribution of pipelines. So, the clusters with a high density of gas pipelines cover a relative smaller area than those with a low density of gas pipelines.

In ArcGIS Pro the area can be divided by creating so called ''polygon feature layers''. A polygon is a fully enclosed area that can be used to specifically analyse the data of other layers within that polygon. For each of the clusters a polygon layer is created and named. These polygon layers can in turn be imported into the other maps or layers to analyse these areas for every separate parameter that is found in part 3.

Hydrogen gas distribution potential
The above clusters can supply, using the current gas assets, a certain amount of gas, whether that is natural gas or hydrogen. By using the data from CBS in which the gas use per household and the number of households are given, the amount of gas use per cluster is calculated (CBS, 2019). As mentioned before the energy density of hydrogen is lower than that of natural gas, but according to several studies, with small adjustments (i.e. increasing the pressure) the assets can supply the same energy content with hydrogen as with natural gas (Sadler, D., Cargill, A., Crowther, M., Rennie, A., Watt, J., Burton, S., Haines, M., Trapps, J., Hand, M., Pomroy, R., Haggerty, K., Summerfield, I., & Evans, 2016) (van der Noort et al., 2017).

It should be noted that the gas use or demand for a certain year in that area doesn't equal exactly the amount of gas that potentially could be exported through that network. But it's expected that it would be a good ballpark figure since the gas demand from year to year is relatively comparable and there should nevertheless be room for fluctuations to deal with the year to year variations. Thereby, there is no data available that gives specific values regarding the amount of gas that can be distributed at the mid and low-pressure level for a certain area.

In ArcGIS pro the polygon layers created can be combined with the CBS data to extract the natural gas demand. This is done with a tool called tabulate intersection, in which you can select one of the polygons and the desired data to get a table with the data for that polygon. This table can be exported into excel and further analysed which was done for each of the polygons. Since not for every household the gas demand was known the average gas demand per households for every polygon was calculated after which this amount was multiplied with the number of households to get the total gas demand.

3.4 Part 3 parameters

This part is carried out in the form of a multi-criteria analysis (MCA). MCA tools are often used to solve problems that are characterized by finding the best choice among alternatives. It is a systematic approach for ranking alternatives against a range of decision criteria. Thereby, both quantitative and qualitative data can be considered, and every parameter can be weighted to incorporate the relative importance of the different criteria.

Since for this problem there is not one best solution the aim is to find the best choices among the alternatives by means of a MCA. In addition, since the parameters are not necessarily relatable to each other using the weighing and scoring method aids in distinguishing the differences between the clusters. The downside to weighing the parameters is that this is done in a subjective manner based on the stakeholder's preferences.

To conduct the MCA the literature is used to find parameters that impact the suitability for hydrogen or all-electric after which these are (when possible) quantified per cluster by using ArcGIS Pro. To give an overall score for every parameter the results are converted to the same scale and given a relative weight which results in an overall ranking.

Deriving the parameters

Parameters that determine the suitability for hydrogen or all-electric are derived by carrying out a literature study. This is done by using scientific literature, case studies like the Leeds City Gate project (Sadler, D., Cargill, A., Crowther, M., Rennie, A., Watt, J., Burton, S., Haines, M., Trapps, J., Hand, M., Pomroy, R., Haggerty, K., Summerfield, I., & Evans, 2016) and by using reports that are conducted in the Netherlands like the studies done by DNV GL and KIWA technology (van der Noort et al., 2017) (Hermkens et al., 2018) . The scientific literature is mainly used to build theoretical knowledge, the case study to learn how this is translated into a more practical case and the Dutch studies are used since parameters that might have an impact in one country could not be significant in another country or the other way around.

Parameters that play a role in the suitability of converting the network into hydrogen or all-electric are considered. These parameters are not only based on whether they impact the suitability for hydrogen or all-electric but also on characteristics or parameters that make it less suitable for one of the two. For instance, the living area of a house does not impact the suitability for hydrogen, but when the area is to small it does have a negative impact on all-electric since there might not be enough space available to install a heat pump.

Quantifying the parameters

After deriving the important parameters the next step was to quantify these parameters per cluster. ArcGIS Pro is used as the main tool to import, analyse and extract the necessary data.

Data sources

The necessary data to quantify the parameters is derived from several sources that have data in a format that can be imported into a GIS software. The data sources are from the municipality of Groningen which has the data regarding the energy labels of the buildings (Gemeente Groningen, 2019). In addition, data from Centraal Bureau voor de Statistiek (CBS) is used in which Groningen is divided into areas with an area of 1 hectare and per area data is shown regarding the population number, the number of households, the electricity and gas use per household and so on (CBS, 2019). The last data source is from Rijksdienst voor het Cultureel Erfgoed, part of the Ministry of Education, Culture and Science in which, amongst other things, the national and municipal monuments are shown (Rijksdienst voor het Cultureel Erfgoed, Ministerie van Onderwijs, 2019). The above-mentioned data sources contain data for either Groningen, the province of Groningen or the Netherlands.

ArcGIS Pro

For every parameter a new map is created in which the polygon layers and the necessary data are imported. In a similar manner as in step 2 in ArcGIS Pro the tabulate intersection tool is used to combine the clusters with the corresponding data for every parameter. After combining the layers for every parameter, the table is exported into excel to further analyse the data. Since in ArcGIS Pro the data is only combined with respect to the right cluster the data is analysed in excel. The way that this is done differs per parameter that was found. In addition, there are points missing in (some of) the datasets and to see whether this amount is significant or not the percentage of data points missing from the total is calculated as well.

Scores per cluster

Comparing the data per parameter between the clusters is relatively easy, but since the parameters all have different values and units, a method is needed that will combine the different parameters to give one overall result. This is done by, for every parameter, grouping the possible outcomes and giving a score per group. For instance, for a house to become all-electric it’s necessary that it has an energy label of at least B or even higher which makes it preferable to convert a cluster with a high percentage of houses that fall into this category into all-electric. Based on this, a cluster with a percentage between 80 and 100% of the houses with an energy label of B or higher, will receive the highest score of 5. Followed by a cluster that has a percentage of between 60 and 80% of the houses with a high energy label and so on.

Table 1 Example of the classification of a parameter

Percentage of energy labels of A++ until B	*0-20 %*	*20-40 %*	*40-60 %*	*60-80 %*	*80-100 %*
Score	1	2	3	4	5

For every parameter the results are grouped into 5 categories and every category corresponds to a score of 1 to 5. This is first done for the parameters for hydrogen and all-electric separately to provide more insight in whether a cluster is suitable for hydrogen because of the parameters that are directly related to hydrogen or indirect due to the parameters that make it unsuitable for all-electric. In both cases a score of 5 means that, for this parameter, it has the highest potential for either hydrogen or all-electric and 1 means the lowest potential.

Weight of every parameter

There are parameters that have a significant impact whether hydrogen or all-electric is suitable and parameters that can have a slightly positive or negative impact. To deal with this, the parameters are given a weight regarding their relative importance. The range for the weight lays between 1 and 5, in which 5 means that the parameter is assumed to have a high impact on the suitability for either all-electric or hydrogen and 1 a low impact. The range between 1 and 5 is chosen since most of the result are not expected to be so specific that developing for instance 10 groups will add to the accuracy of the results. Assessing these weights is based on the literature study done and insights gained. This is done since these parameters can't quantitively be compared, even if you would ask several experts it's expected that their outcome will (slightly) differ as well.

Ranking

For every parameter the 1 to 5 score per cluster is known and by multiplying this with the weight of the parameter the result is calculated. To give more insight in the data this is first calculated for the parameters that impact the suitability for hydrogen and all-electric separately. After which these are combined to give the final ranking. An example of what the ranking would look like can be found in Table 2.

Table 2. Example final ranking clusters

	Weight	*Cluster 1*	*Result cluster 1*	*Cluster 2*	*Result cluster 2*	*Etc.*
Parameter 1	*2*	3	6	5	10	
Parameter 2	*1*	4	4	2	2	
Etc.	..	..	..			
Final result			10		12	

3.5 Final part: Hydrogen/all-electric configuration of clusters

In the final part the results of parts 1,2 and 3 are combined to, based on the forecasted hydrogen demand, the gas distribution potential and the ranking, give an optimal configuration of the clusters per scenario.

Hydrogen/all-electric configuration of clusters

Since every scenario has different specifications regarding the hydrogen demand, the gas distribution potential per cluster can be used to define per scenario which clusters can supply the amount of hydrogen forecasted by the scenarios. Based on both the distribution potential of a cluster and the ranking per scenario the most suitable configuration will be developed. This implies that the clusters that are ranked as the best options for hydrogen might not necessarily be the ones that are converted to hydrogen since this will also be based on the amount of hydrogen that can be distributed by the cluster.

For instance, say in a scenario an amount of 30 million m^3 hydrogen needs to be supplied per year and the ranking of the clusters could look like Table 3. This means that by converting cluster 1 until 3 this would lead to a hydrogen amount of 24 million m^3 which will not be sufficient, so cluster 4 needs to be added leading to an amount of 32 million m^3. In this case a better option would be to convert cluster 1,2 and 4 which can provide the amount needed with a smaller conversion area. Generally, the amount of hydrogen that is distributed in every configuration should lay within a 5% margin of the hydrogen demand that is calculated in a scenario to be able to develop a well-directed configuration.

Table 3 Example of the ranking of the clusters and amount of hydrogen needed

Cluster	*Points*	*Amount of hydrogen (million m^3)*
1	25	10
2	21	12
3	7	2
4	2	8

3.6 Overview of the method

In part 1 the values of the 3 scenarios are converted to values for Groningen to determine the hydrogen demand in 2050 per scenario. In part 2, based on the gas network, Groningen is divided into 8 areas that could potentially be converted into hydrogen and all-electric and per cluster the distribution potential is calculated. In part 3 the parameters that impact the suitability for hydrogen/all-electric are defined, quantified and given a weight per cluster to reach an overall ranking. The last part is to combine the hydrogen demand with the distribution potential and the cluster ranking to be able to develop the best configuration per scenario.

4. Results

4.1 Part 1. Scenarios

Hydrogen

Energy demand

Since the amount of energy that (bio)methane can provide will be covered by hydrogen the total amount of energy that will be provided by hydrogen will be the combined amount of hydrogen and (bio)methane which is shown in Table 4.

Volume

With the values for the energy demand for hydrogen the corresponding volume of gas is calculated which can also be found in Table 4.

Table 4. Hydrogen demand per scenario for the Netherlands (energy and volume)

	Local	*National*	*International*
Hydrogen demand (TWh)	20	48	53
Hydrogen volume (million m^3)	2047,2	4913,3	5425,1

Groningen

With the 2018 population data and the forecasted data from CBS regarding immigration and urbanization *Table 5* is created. The numbers that were not a prediction by CBS are the bold values. CBS forecasted that the population size in 2040 in Groningen would be 214.000 which is around 1,182% of the forecasted total Dutch population size in 2040. Since there is only a small increase in population size between 2040 and 2050 it is assumed that this percentage will roughly remain the same for 2050. With that percentage the population size of Groningen is calculated and expected to be around 0,219 million in 2050.

Table 5. Population prognosis

x million	*01-01-2018*	*01-01-2040*	*01-01-2050*
Netherlands	17,18	18,1	18,5
Groningen	0,203	0,214	**0,219**
Percentage	1,180%	1,182%	**1,182%**

Final hydrogen demand Groningen

With use of *Table 5*, regarding the calculated population size, the energy, electricity and hydrogen demand are converted to the values for Groningen which can be found in *Table 20* in appendix C. In addition the hydrogen volume that was calculated in Table 4 is used to convert the values to the values for Groningen which are shown in Table 6. These values are the input values to develop the different configuration per scenario.

Table 6. Hydrogen demand per scenario for Groningen

	Local	*National*	*International*
Hydrogen volume (million m³)	24,19	58,06	64,11

Main results part 1

It's expected that in 2050 around 1,182% of the Dutch population would live in Groningen which is an expected increase of 16.000 inhabitants for Groningen compared to 2018. Taking the scenarios into account, the national and international scenario have a relatively similar hydrogen demand in 2050. The hydrogen demand for the local scenario is even more than 2 times as small. This is not an unexpected outcome since the local scenario is focused on a self-sufficient and decentralised Dutch energy system while using hydrogen requires an extensive infrastructure which is better suited in a centralised system. In the local scenario hydrogen will be mainly used in small-scale projects and is thus not able to reach the same potential as in the national and international scenario.

4.2 Part 2: Gas Clusters

Main gas supply pipelines

By adding constraints to the data regarding the pressure and pipe diameter, the main gas supply pipelines are distinguished. As can be seen from Figure 5 and Figure 6 compared to the original data shown in Figure 4 only a few pipelines remain that meet the given pressure and pipe diameter constraints.

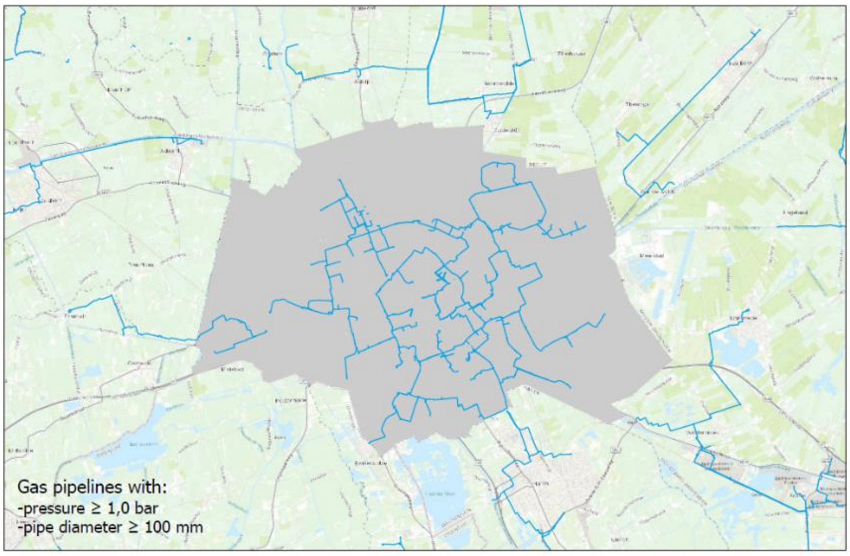


Figure 5. Gas pipelines with a pressure ≥ 1,0 bar and a pipe diameter ≥ 100 mm

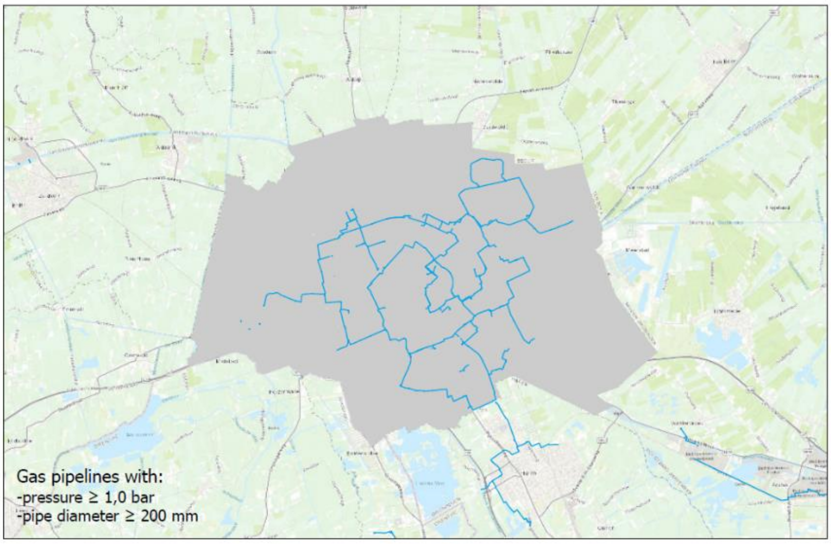


Figure 6. Gas pipelines with a pressure ≥ 1,0 bar and a pipe diameter ≥ 200 mm

To validate this data the gas transport map of the TSO Gasunie was used which can be found in Figure 16 in appendix C in which the regional and main pipelines are shown. In the gas transport map the regional pipelines that supply gas to Groningen correspond with the locations of the supply pipelines in Figure 5. In addition, there is only one main pipeline shown in this gas transport map that distributes gas to Groningen which corresponds with the only gas supply pipeline that is still shown in Figure 6 when the constrains of the pipe diameter is set on ≥200 mm instead of ≥100 mm.

Gas clusters

Using the main pipelines, the system is divided into 8 clusters as can be seen in Figure 7. The borders of the clusters are in general close to the main pipelines to make use of the existing gas assets. In addition, the areas in the centre are generally smaller since, based on the density of the pipeline network, it's expected that these are more populated than the outskirts.

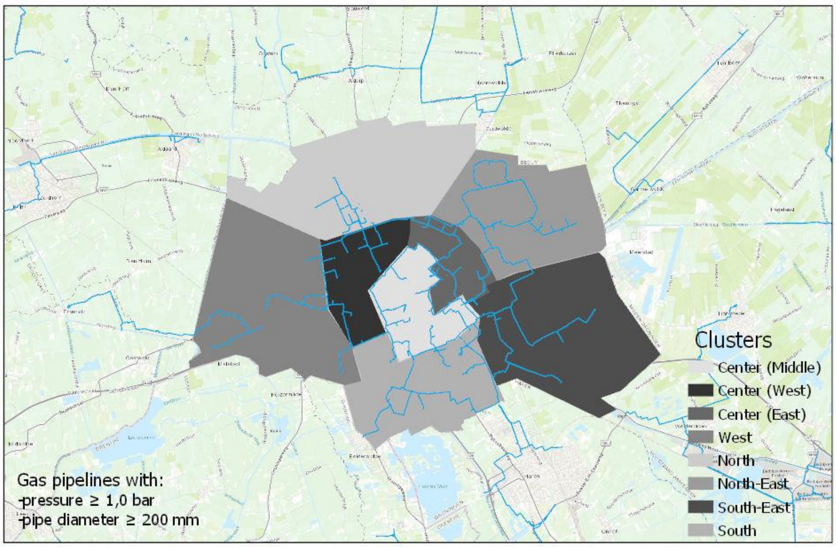


Figure 7. Gas clusters

To give more insight in the characteristics of the clusters, in Figure 8 per square kilometre the inhabitants are shown. As expected, in the clusters in the center the population density is higher, but in Center (West) there is also quite a significant part that has no habitants or only a few. In addition, there is quite a significant difference between the population density in the outskirts. Especially the South and North-East have quite a high population density compared to the North. In Table 21 in appendix C more information can be found regarding the area and number of households per cluster.

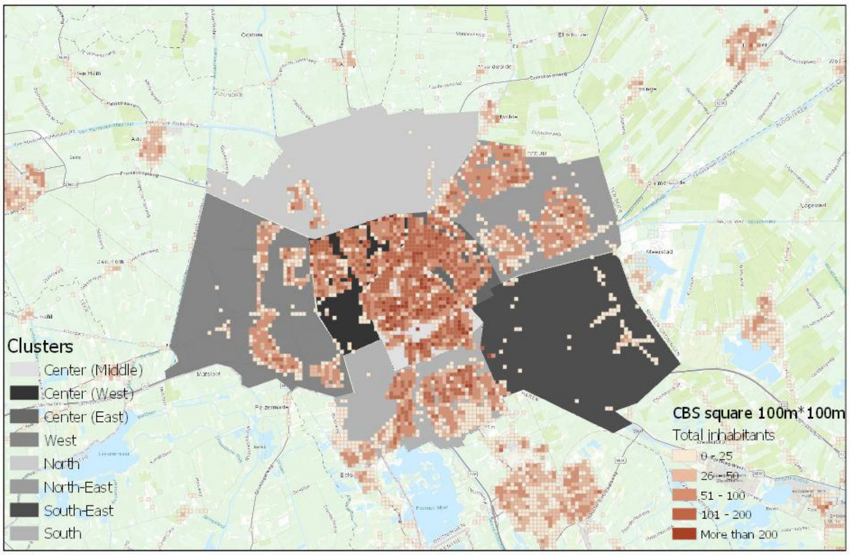


Figure 8. Population density per square km

Gas distribution potential

Per cluster the gas distribution potential is calculated to use in the final part to develop the three configurations of the clusters. As expected, considering the characteristics of the clusters mentioned before, there is quite a significant difference between the clusters. Especially the clusters in the center have a high gas distribution potential compared to North and South-East.

Cluster	*Gas distribution potential (million m^3)*
Center (Middle)	59,9
Center (West)	24,3
Center (East)	30,5
West	8,5
North	1,7
North-East	19,2
South-East	1,1
South	23,3

Main results part 2

With the use of the gas pipelines 8 clusters were formed. The clusters in the centre cover a smaller area than the clusters that form the outskirts of the city, with the aim to form relatively comparable clusters regarding the gas distribution potential. However, it was found that the gas distribution potential of every clusters still differs significantly even though the clusters in the Center only cover 1/3 of the area of those in the outskirts. The Center (Middle) has the highest distribution potential of 59,9 million m^3 and the South-East the lowest of 1,1 million m^3.

4.3 Part 3: Parameters

Five parameters were found that impact the suitability for hydrogen and all-electric. Each one of them is explained and quantified per cluster below.

Parameter 1: Supply area

The gas network is called a network for a reason; all the areas are connected to each other so that the gas can be distributed to every single household. To make sure that the gas assets are used efficiently it's important to know which clusters are a supply area for other cluster. To make sure that no area is cut off that used to be the main supply area for the other parts or clusters of the network. One of the parameters will thus be whether an area is a supply area for other areas or not.

By using the gas transport map from Gasunie, which can be found in Figure 16 in appendix C, and Figure 7 the main supply areas are distinguished and shown in Figure 9. The red arrows indicate where the gas stream enters Groningen, the thicker arrow in the South shows the area where both a main pipeline and the regional pipelines supply gas and is thus considered the most important supply area out of the three.

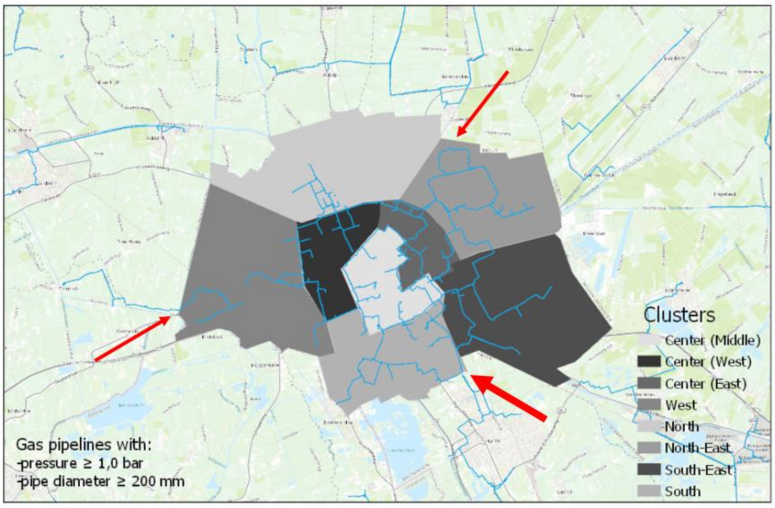


Figure 9. Main supply areas

Score

Since the south is the main supply area it is given the highest score of 5, followed by the other two supply areas with a score of 4. The next criterium is whether an area is connected to one or two supply clusters, when it is only connected to one supply cluster a problem might evolve when that supply area is cut off. So, when it is only connected to one supply cluster it is given a score of 1 which are Center (Middle) and Center (East). When it is connected to two areas it is scored 2, which are Center (West), North and South-East.

Table 7. Scores parameter 1

	Center (Middle)	Center (West)	Center (East)	West	North	North-East	South-East	South
Score	1	2	1	4	2	4	2	5

Parameter 2: Energy label of buildings

As stated in section 2.3, for a heat pump to work effectively and to be able to reach the desired temperature, buildings need to have a certain level of insulation corresponding to an energy label B or higher. In ArcGIS Pro data regarding the energy labels is imported and combined with the clusters as shown in Figure 10.

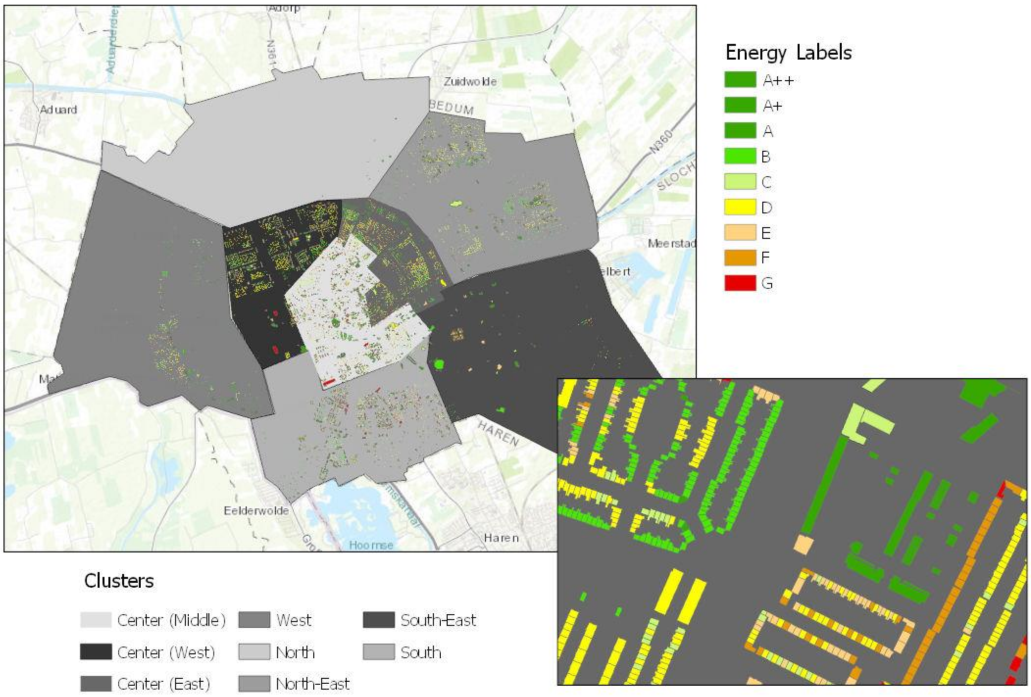


Figure 10. Distribution of energy labels of houses in Groningen

A more detailed graphical representation of the percentage of every energy label per clusters can be found in Figure 17 in appendix C. Since for this purpose it is mostly relevant whether the energy label meets the requirements for heat pumps a distinction is made between energy labels A++ until B and C until G which can be found in Figure 11.

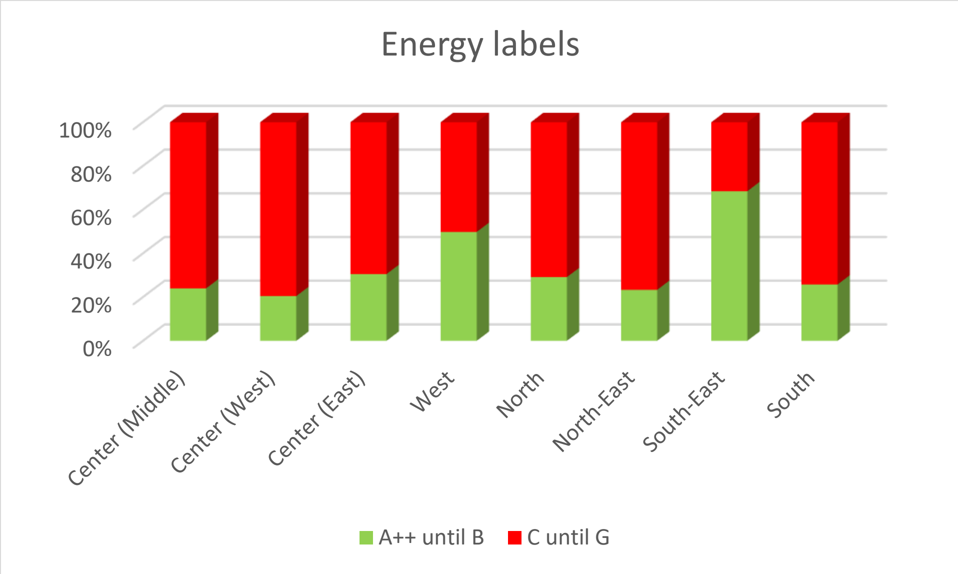


Figure 11. Distribution of energy labels A++ until B and C until G of houses in Groningen

As can be noted there is a significant difference between certain clusters, in the Center (West) only 20% of the buildings have an energy label of B or higher compared to 68% in South-East. In general, in the clusters in the center the energy labels are relatively poor which is expected since the center area in Groningen consist of relatively old buildings.

Since only buildings with a label A++, A+, A and B have enough insulation to become all-electric without further adaptations regarding the insulation, the ranking is done based on the percentage of houses with such a label. An area with a percentage between 0 to 20% of the houses with an energy label of A++ until B will receive a 1 and so on. The higher the percentage of energy labels of A++ until B the higher the score.

Table 8. Scoring table parameter 2

Percentage of energy labels of A++ until B	*0 until 20%*	*20 until 40%*	*40 until 60%*	*60 until 80%*	*80 until 100%*
Score	1	2	3	4	5

With the scoring table in Table 8 the percentages of the energy labels per clusters are converted to a score between 1 and 5 as can be seen in Table 9.

Table 9. Scores parameter 2

	Center (Middle)	Center (West)	Center (East)	West	North	North-East	South-East	South
Percentage of energy labels of A++ until B	24%	20%	31%	50%	29%	23%	68%	26%
Score	2	1	2	3	2	2	4	1

Parameter 3: Average area house

Heat pumps need more space in- and outside the house, while hydrogen could replace natural gas in all the current appliances and sacrificing available space is not an issue. In addition, heat pumps can lead to potential noise disruption in a small living space and in some cases, a heat pump might not even be an option due to infrastructural challenges. This is often the case in flat like buildings where there is limited interior and exterior space, no lofts to run pipework and no easy access to the multi-story buildings. So, with a smaller area the building structure complicates the implementation of heat pumps and one is less likely to install a heat pump.

In the same data set as the one for the energy labels the type of buildings is also included and with the data of Agentschap NL, per type of building the average area is known. A graphical representation of the distribution of the type of houses per cluster and the average area per type of house can be found in Table 22 in appendix C. The average area is between 68 square meters for a tenement house and 150 square meters for a detached house.

An option to calculate the score is to calculate the average area of the total set of houses per cluster. However, by averaging in that way a lot of valuable data will be lost, since a cluster might contain a large number of detached houses which will significantly increase the average score but might only comprise a small sample of the total of households that can easily become all-electric. To deal with this, the type of house is first given a score based on Table 10, per type of house the result can be found in Table 22 in appendix C. The total number of every house type per cluster is multiplied by this score and afterwards averaged which gives the results in Table 11. As expected, the outskirts like North and West have a higher score than the Center parts since in outskirts there is in general more room available.

Table 10. Scoring table parameter 3

Average area house (m^2)	*Smaller than 80*	*80-90*	*90-100*	*100-110*	*110+*
Score	1	2	3	4	5

Table 11. Scores parameter 3

	Center (Middle)	Center (West)	Center (East)	West	North	North-East	South-East	South
Score	1,6	1,8	1,9	3,6	4,8	2,7	2,2	1,7

The data set also contained two other groups, others and buildings with assisted living, these are both excluded from the data since it's not possible to quantify the group others in terms of the area and for buildings with assisted living the data from Agentschap NL did not include this group. These two groups only comprised 1,34% of all the data and are thus relatively small.

Parameter 4: Monuments

The fourth parameter is based on the relative number of monuments in a cluster. Regarding renovating or adjusting monuments there are a lot of rules and regulations in the Netherlands. Installing a heat pump and/or improving the insulation in a monument is possible but not as easy as it is with other buildings. So, the more monuments there are in an area the costlier and harder it will be to become all-electric. In Figure 12 the national and municipal monuments are shown per cluster based on the data from the Ministry.

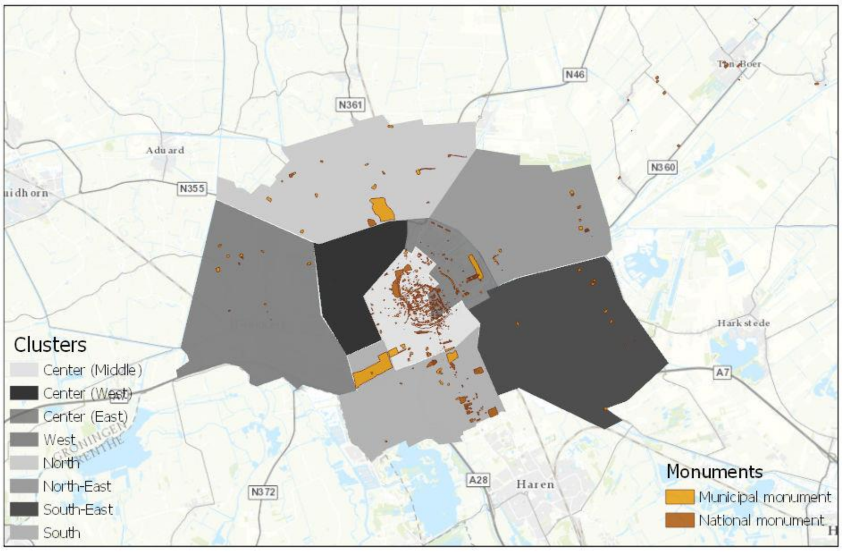


Figure 12. Monuments

With the CBS data regarding the number of houses and the data regarding all the monuments, the percentage of monuments per cluster is calculated. Unfortunately, it is not stated in the data set whether a monument is currently used as a house or for any other purpose. However, at the end of 2018 according to CBS, 58,6% of all the monuments are marked as inhabited buildings. The score is multiplied by 58,6% to get the percentage of houses that are labelled as a monument per cluster.

Table 12 shows the scoring table that is developed based on the results. The results showed that most of the time the percentage of the houses that are a monument is less than 2%. In Groningen only the North has a significant higher percentage which is regarded as an exception. Based on the scoring table the scores per cluster are calculated in shown in Table 13.

Table 12. Scoring table parameter 4

Percentage of monuments	*Less than 1%*	*1-2%*	*2-3%*	*3-4%*	*More than 4%*
Score	1	2	3	4	5

Table 13. Scores parameter 4

	Center (Middle)	Center (West)	Center (East)	West	North	North-East	South-East	South
Result	4,60%	0,03%	1,59%	0,49%	55,81%	0,18%	1,90%	0,54%
Score	5	1	2	1	5	1	2	1

Parameter 5 Possible congestion of the electricity network

To be able to meet the electricity demand it's likely that the electricity network needs to be expanded. This expansion requires space for assets like cables and transformers. In general, areas that have the highest electricity demand have the least available space. To quantify this for the clusters, the average electricity use per square kilometre per cluster is calculated. The cluster with already the highest electricity demand is thus less suitable to become all-electric due to possible congestion of the electricity network.

By using the CBS data regarding the electricity demand per household and the number of households the average electricity demand per household per cluster is calculated. For 0,11 % of the households the electricity demand is not known, so with the average electricity demand and the number of households the total electricity demand of every cluster is calculated. For comparison between the clusters the electricity demand is calculated per square kilometre and given a score based on Table 14.

Table 14. Scoring table parameter 5

Electricity demand (GWh / km^2)	*Less than 5*	*5-10*	*10-15*	*15-20*	*More than 20*
Score	1	2	3	4	5

The results are stated in Table 15, as expected especially the center parts have a higher score since these areas are densely populated and comprise older buildings so the electricity use per km^2 is significantly higher.

Table 15. Scores parameter 5

	Center (Middle)	**Center (West)**	**Center (East)**	**West**	**North**	**North-East**	**South-East**	**South**
Result	17,9	7,5	13,7	1,2	0,3	3,3	0,1	4,0
Score	4	2	3	1	1	1	1	2

Weighing

In Table 16 first an overview of the parameters and their weight is given, after for every parameter the reasoning behind this score is explained. The parameters are quite diverse, some are based on the gas pipelines, some on the characteristics of hydrogen, some on all-electric and some on the building infrastructure.

Table 16. Weight of every parameter

Parameter	*Weight*
Parameter 1 Supply area	2
Parameter 2 Energy label	5
Parameter 3 Type of building (area)	4
Parameter 4 Monuments	1
Parameter 5 Possible congestion of electricity network	2

Parameter 1 Supply area

To make efficient use of the existing assets this parameter is important, when for instance an area in the center that is further away from a supply area is converted into hydrogen the pipelines in the supply cluster are still needed to reach this area. On the other hand, in part 2 the clusters are designed in such a way that the main pipelines could often be used by at least two clusters and since it turned out that there are 3 supply areas every area is relatively close to one of these areas. Taking everything into consideration this parameter is given a weight of 2 out of 5.

Parameter 2 Energy label
The highest weight is given to the parameter energy labels. For a heat pump to function a building needs to have a minimum energy label of B, but preferably even higher. Since implementing a heat pump is already quite an expense, if in addition the house needs to be renovated to improve the energy label this option becomes even costlier. Which parties will need to bear this cost is not part of the study, but in general the costlier and more effort it will take the harder a technology will be to implement. An area that already has a higher percentage of energy labels will be a lot easier to convert. That is why this parameter has been given a high weight of 5.

Parameter 3 Type of building (area)
Below a certain surface area a heat pump might for a household not be a preferred or even viable option. The average area of a house is not likely to increase but a heat pump is still a relatively new technology, so the size and features are expected to improve and decrease in size. However, since it is still quite uncertain what these developments could entail, and it is quite certain that the area of the existing buildings in general will not increase this parameter is given a weight of 4.

Parameter 4 Monuments
Due to rules and regulations monuments will not be the easiest to adjust. There are certain additional aspects that need to be considered and every house or building needs a custom-made plan which increases the cost. This should be kept in mind but considering the relatively small amount of buildings that are monuments and, although it might be harder, these building can still be converted, this parameter has been given the lowest weight of 1.

Parameter 5 Possible congestion of the electricity network
The congestion of the electricity network could become a problem when an area is converted to all-electric and capacity needs to be added to the network. Luckily Groningen is relatively spacious compared to other cities like Amsterdam, so it will have an impact but is not expected to create an insurmountable bottleneck for an all-electric area yet. So, this parameter is given a weight of 2.

Ranking
In Table 17 the scores per parameter after adding the weights are shown. The italic values are the parameters that have a positive impact on the suitability for all-electric. The other values have an (indirect) positive impact on conversion to hydrogen. An indirect positive impact on hydrogen means that for the actual conversion to hydrogen this parameter will not actually influence anything, but since the parameter has a negative influence on all-electric this makes it more suitable for hydrogen. For instance, whether there are lot of monuments in an area does not influence the way hydrogen can be implemented, but it does influence (negatively) how easy it is to convert a cluster into electricity. That’s why, since there are only two options, the parameters that have a negative impact for all-electric are considered as having a positive impact on hydrogen.

The two parameters that have a positive impact for all-electric are added and the three scores that either have a positive impact on hydrogen or a negative impact on all-electric are added as well. This is done to form two groups. Since one cluster can either be converted to hydrogen or all-electric the separate scores need to be combined as well, this is done by subtracting the electricity score from the hydrogen score. So, a high hydrogen score and a low electricity score will lead to the most suitable hydrogen cluster and a low hydrogen score and high electricity score will lead to the most suitable all-electric cluster. The highest overall hydrogen score is in this case the South which means that this cluster is most suitable for hydrogen and the lowest score is the South-East which is thus best for electricity. The highest value in the overall score will thus both include the aspects regarding the suitability for hydrogen, but in addition when it is suitable for electricity this will reduce the overall score.

Table 17. Overall scores per parameter and cluster

	Center (Middle)	*Center (West)*	*Center (East)*	*West*	*North*	*North-East*	*South-East*	*South*
Parameter 1: Supply area	2	4	2	8	4	8	4	10
Parameter 2: Energy label	*10*	*5*	*10*	*15*	*10*	*10*	*20*	*5*
Parameter 3: Type of building (area)	*6,4*	*7,2*	*7,6*	*14,4*	*19,2*	*10,8*	*8,8*	*6,8*
Parameter 4 Monuments	5	1	2	1	5	1	2	1
Parameter 5 Possible congestion of electricity network	8	4	6	2	2	2	2	2
Hydrogen score	15	9	10	11	11	11	8	13
All-electric score	16,4	12,2	17,6	29,4	29,2	20,8	28,8	11,8
Overall score	-1,4	-3,2	-7,6	-18,4	-18,2	-9,8	-20,8	1,2

In the table the blue shaded results are the clusters that are most suitable for conversion into hydrogen and the grey shaded results are most suitable for all-electric. As can be seen by adding the separate scores the overall score shows quite similar results as the two separate scores. This means that when for instance only the parameters that impact the implementation for hydrogen or all-electric would be considered similar results would be found.

For hydrogen, the Center (middle) turned out to be number one and South number two and in the overall score these are switched. Since for the hydrogen score there are 3 clusters with a number 3 position these are not highlighted.

For all-electric, West, North and South-East form the top 3 and the results are relatively close to one another, which is also the case in the overall score.

Main result part 3

Five parameters were found that impact the suitability for either hydrogen or all-electric. These are the main supply area, energy label, type of building (area), monuments and possible congestion of the electricity network. It's expected that of these parameters the energy label will impact the suitability for hydrogen/all-electric the most as compared to monuments which is thought to have the least impact. It was found that the cluster South and Center (Middle) are the most suitable clusters to convert to hydrogen and the clusters West, North and South-East are most suitable for electricity with relatively small differences between the three clusters.

4.4 Final part: Hydrogen/all-electric configuration of clusters

With the hydrogen demand per scenario, the hydrogen distribution potential per cluster and the ranking of the cluster the configurations are developed as can be seen in Table 18. Here the clusters that will be converted to hydrogen are coloured blue. Per scenario explained in section 2.5 a cluster configuration has been developed. The local scenario is quite straightforward, cluster South can provide (within the 5% margin) the right amount of hydrogen.

For the national scenario this is less straightforward, when South would be considered the best configuration that would lead to the right amount would be to convert clusters South, Center (West), North and West. Since half of these clusters fall in the lower part of the ranking it is preferred to only convert the second-best cluster which is Center (Middle).

For the international scenario clusters South, Center (West) and North-East will be converted to hydrogen. Another option would be to convert Center (Middle) and North but since South is ranked number 1 and North number 6, the first configuration is preferable.

Table 18. Configuration of clusters per scenario

		Local	*National*	*International*
	Hydrogen gas volumes (million m^3)	24,2	58,1	64,1
1. South	23,3			
2. Center (Middle)	59,9			
3. Center (West)	24,3			
4. Center (East)	30,5			
5. North-East	19,2			
6. North	1,7			
7. West	8,5			
8. South-East	1,1			
Sum	168,6	23,3	59,9	66,8
% of total		13,8	35,6	39,6

The cluster configuration for each scenario is given in Figure 13, Figure 14 and Figure 15. For the local scenario the supply area would be South and the other two supply areas could be cut-off. In the national scenario the converted cluster is not one of the supply clusters and thus the main-pipelines that will supply the hydrogen through one of the all-electric clusters are still needed. South is the main supply area and it is the only one that is directly connected to the Center (Middle) so the main pipeline in the South will be used to transport the hydrogen to the Center (Middle).

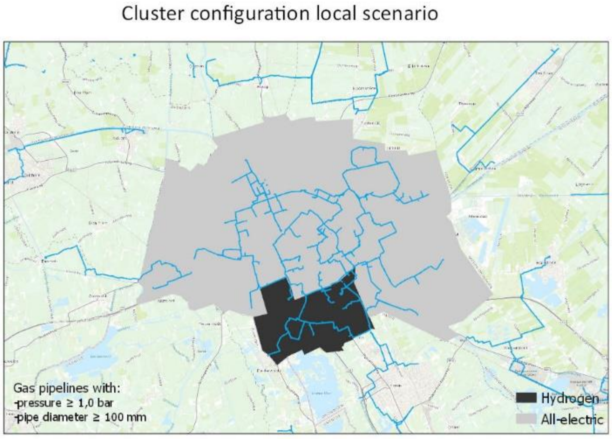


Figure 13. Cluster configuration local scenario

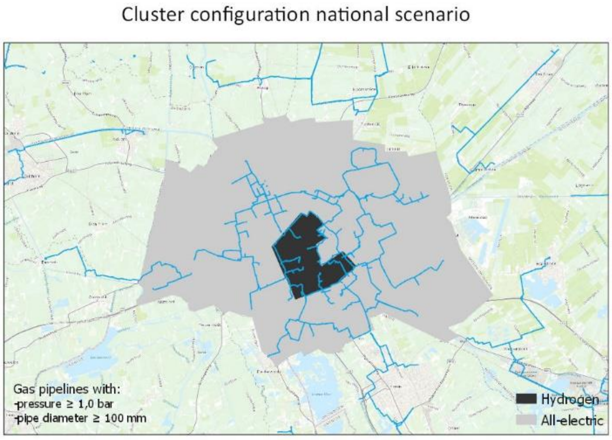


Figure 14. Cluster configuration national scenario

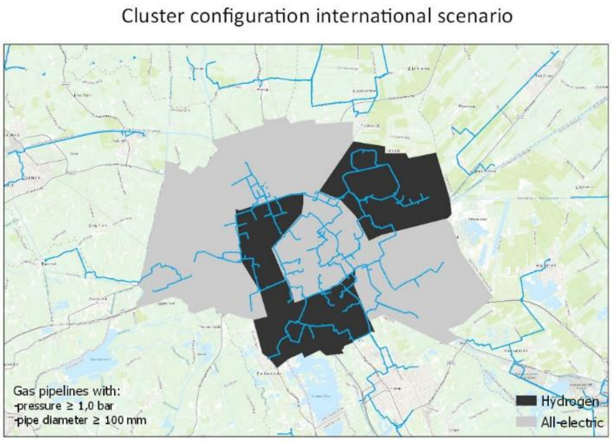


Figure 15. Cluster configuration international scenario

Main results Final Part: Hydrogen/all-electric configuration of clusters

It was found that when combing all the inputs from the three parts the configurations would not necessarily result in a configuration where all the cluster with the highest hydrogen score would be converted to hydrogen. This is mainly due to the relatively big difference between the gas distribution potential of the clusters. Only in the national scenario the converted cluster(s) are not a supply area or directly linked to a converted supply area so in that case (part of the) gas pipelines in the South cluster would still be needed for the distribution of hydrogen. Since this cluster is converted to hydrogen in both the local and international scenario it's expected that when hydrogen would be used in the gas assets this would be the most important cluster to consider. For the local scenario 13,8% of the gas assets will be converted, for the national scenario 35,6% and for the international scenario 39,6%.

5. Discussion

Contribution to established knowledge

Using hydrogen as an energy carrier in the gas network has gained a lot of attention as one of the options towards a natural gas free society in 2050. The focus of these studies is on the safety issues, how the hydrogen will be produced and what amount needs to be produced to meet the demand. In addition, regarding a natural gas free society there are several case-studies conducted by municipalities to show how a city can become natural gas free in 2050, but none of these studies have considered using hydrogen in the current gas network as one of the options.

For the transition to become more tangible and concrete, this study is done to develop several network configurations for a city like Groningen, in which some clusters will be converted to hydrogen and others will become all-electric. By taking these configurations into account stakeholders like DSOs and households can already adapt to these changes. DSOs could make more substantiated decisions regarding investment in the electricity and gas infrastructure and a household can choose to not invest in a new boiler when their house needs to become all-electric within a couple of years.

In addition, this is the first study that uses the extensive gas assets as a starting point for the development of the clusters as opposed to using the general neighbourhood demographics that are easier to use but don't have any added value for the research. Using the existing assets efficiently will lower the investment needed in terms of resources, workload and costs.

Even though this study is done for Groningen it could easily be used as a framework for other cities in the Netherlands since the parameters that were found apply to every city in the Netherlands. This study can thus be an example of what an all-electric/hydrogen configuration could look like and it can be used as a framework for other cities.

Research limitations

In this study three main limitations were found. The first one is that only all-electric and hydrogen are considered as the possible 2050 alternatives. Other alternatives like geothermal and district heating are not considered due to the scope of this study but could also be viable alternatives to complement the future energy mix. However, both geothermal and district heating are quite location dependent since the energy demand preferably needs to be close to the energy source, so including those alternatives could be relatively easy. By prioritizing the optimal locations for the above-mentioned alternatives and converting the rest of the network into either hydrogen or all-electric a complete configuration could be developed.

The second research limitation is that the weighing of the parameters can only be done in a relative subjective way. An option to deal with the subjectivity of using weights for parameters is to average experts' opinions. However, since the parameters found cover quite a broad spectrum it was expected that experts will have more focus on certain elements based on their background. For instance, an expert that works for a DSO will likely put more emphasize on a parameter that has to do with the current gas assets as opposed to parameters that have to do with the building infrastructure.

Thereby, as is often the case with complex problems there is not one unique optimal solution and the aim of performing a multi-criteria analysis is to differentiate the possible solutions. Based on the decision-maker's preferences it is relatively easy to adjust the weights to see whether it will influence the outcome. So, in this preliminary stage of the research it's expected that one independent weighing can give enough insights but based on the preferences of future stakeholders the weights could easily be adjusted.

Finally, since the aim of this study was to use the existing gas assets as the starting point for the clusters there is quite a demographic difference between the clusters. Even though beforehand it was expected that the areas in the center would be more densely populated and therefore these clusters in general only cover 1/3 of the area of that of a cluster in the outskirts there is still a significant demographic difference. For instance, the cluster Center (Middle) covers an area of 5,5 square kilometre and has over 40.000 households compared to the cluster South-East that covers an area of 16,1 square kilometre with only 615 households.

Especially for the clusters that turned out to contain a significant number of households a division of these clusters into smaller clusters would make the conversion more manageable and specific. On the other hand, care should be taken with creating a lot of smaller clusters since converting the gas pipelines of several small clusters into hydrogen pipelines will not be optimal. This will (potentially) require converting a significant amount of the gas assets to be able to reach all these scattered clusters and thus counteracts the purpose of using the existing gas assets effectively.

Further research

The conversion of a whole city will not happen overnight, so the next step would be to study how clusters can be converted over time. This may sound straightforward but is expected to be quite a challenge. There are a lot of things that should be considered. First, when a cluster would be converted the production capacity for either hydrogen or electricity should be sufficient to meet the demand. Second, the conversion of a cluster would imply significant (gas and electricity) infrastructural changes. Since the infrastructure reaches up to and even inside the buildings the inclusion and co-operation of households is required. Lastly, depending on the conversion to all-electric or hydrogen, houses need to be (significantly) adapted which will and cannot be done for a whole area overnight.

This study focused mainly on the technical aspects regarding the conversion towards hydrogen or all-electric. Naturally, there are other important aspects involved like the cost of the conversion and whether there is public acceptance for this conversion. The conversion of a whole city will be costly, but further research is needed to show the cost implications per scenario. Regarding the public acceptance, since hydrogen is highly flammable it could be received by the public as dangerous which could result in a lot of opposition. The impact of a negative perception of the public towards a technology could be significant and is thus important to study further.

These types of studies are mostly conducted by municipalities, but which party will oversee these large-scale projects and who will bear the costs is not clear yet. The government tries to steer the energy transition with the climate agreements but for it to happen a clear and concise plan for such a conversion needs to be developed. So, further research is needed focused on the stakeholders involved, their responsibility and regarding the cost distribution.

Leading a complete country like the Netherlands or even a city like Groningen away from using natural gas when currently 82% of the households are connected to the gas network is an incredible task. Even though there are several limitations and further research is needed, this study it is a good starting point to show a more concrete pathway towards this goal. It also showed that there is not one silver bullet, but that alternatives have advantages and disadvantages and that by taking these into account assets can be used in a smarter way. In addition, by showing the complexity of the problem one should realize the importance of starting as soon as possible.

6. Conclusion

The gas network is divided into eight suitable clusters based on the pipeline density, location, pressure and pipe diameter of the pipelines. The pipelines that have a higher pressure and larger pipe diameter can distribute a larger gas volume and are considered as the main pipelines in the low-and medium pressure network. Based on these pipelines eight clusters are formed in a manner that the border of a cluster is close to one of the main pipelines to make optimal use of the assets. The gas assets in every cluster distribute a certain amount of gas to the households. Per cluster there is quite a significant difference in the gas distribution potential ranging from 1,1 million m^3 for the South-East until 59,9 million m^3 for the Center (Middle).

Five parameters were found that determine whether the cluster is suitable for hydrogen or all-electric. These are divided into two groups, whether the parameter has a positive impact on hydrogen or all-electric. Since there are only two options for each cluster, a negative impact on all-electric will consequently lead to a positive impact for hydrogen.

The three parameters that lead to a positive score for hydrogen are the supply area, monuments and possible congestion of the electricity network. Whether a cluster is (close to) a supply area will positively impact the hydrogen score since in that case the gas does not need to be distributed through other clusters that are not converted into hydrogen. When there is a high number of monuments this cluster might be more suitable for hydrogen as well, since, due to rules and regulation, it will be harder to convert a monument to all-electric as opposed to hydrogen which can be used in a similar manner as natural gas. The last parameter is the possible congestion of the electricity network in densely populated areas, which might cause problems when more and more electricity needs to be distributed and hydrogen will in that case thus be a more suitable option.

When an area has a relative high percentage of energy labels A++ until B this will facilitate the conversion to all-electric and it's thus regarded as positive for all-electric. The composition of the type of buildings in a cluster is the other parameter since this can be used as an indication regarding the available area that could potentially be used to install heat pumps. Since a heat pump requires space, the larger the area the more likely a heat pump can and will be installed. By means of a multi-criteria analysis every parameter is given a weight to show the relative importance. The parameter, energy labels, has been given the highest weight and monuments the lowest.

Based on the ranking of the gas clusters it was found that in general the clusters that are densely populated, consist of older buildings, and have a high number of multi-story buildings like gallery flats and tenement houses are the optimal cluster to convert to hydrogen. These types of clusters are generally found in the old center of cities. Clusters that are sparsely populated, consist of newer buildings and have a high number of semi-detached or detached houses are most suitable to become all-electric. These are often found in the outskirts of the cities.

Based on the ranking and the gas distribution potential per cluster, per scenario from Netbeheer Nederland, the right configuration for 2050 was developed. It was found that every configuration is quite different since not only the ranking is considered but also the gas distribution potential of every cluster to be able to distribute within a certain margin the right amount of hydrogen that was calculated for every scenario.

How the conversion of the gas network can evolve will depend highly on which scenario is considered. For the local and national scenario converting only one cluster will lead to enough hydrogen as opposed to the international scenario where three clusters are converted. Since the local scenario is mainly based on a self-sufficient and decentralized energy system this is not in line with converting only one cluster to hydrogen. It's expected that in the local scenario hydrogen will be used in a more decentralised manner by for instance using fuel cells. Therefore, it is expected that when hydrogen would be used in 2050 in the gas assets the network would more likely evolve in either the national or international scenario.

In the national scenario 35,6% and in the international scenario 39,6% of the gas assets will be converted to hydrogen. This both implies that a big portion of the gas assets will be depreciated the coming decades, and that the electricity infrastructure will need a significant investment to be able to meet the 2050 demand. So, with both the national and international scenario drastic infrastructural investments are needed to meet the demand for hydrogen and electricity in 2050. To meet the energy demand for the households in 2050, without the use of natural gas, drastic steps will need to be taken to be able to reach this goal. Hydrogen can form an integral part of the conversion but is not the silver bullet and should thus be considered as one of the alternatives.

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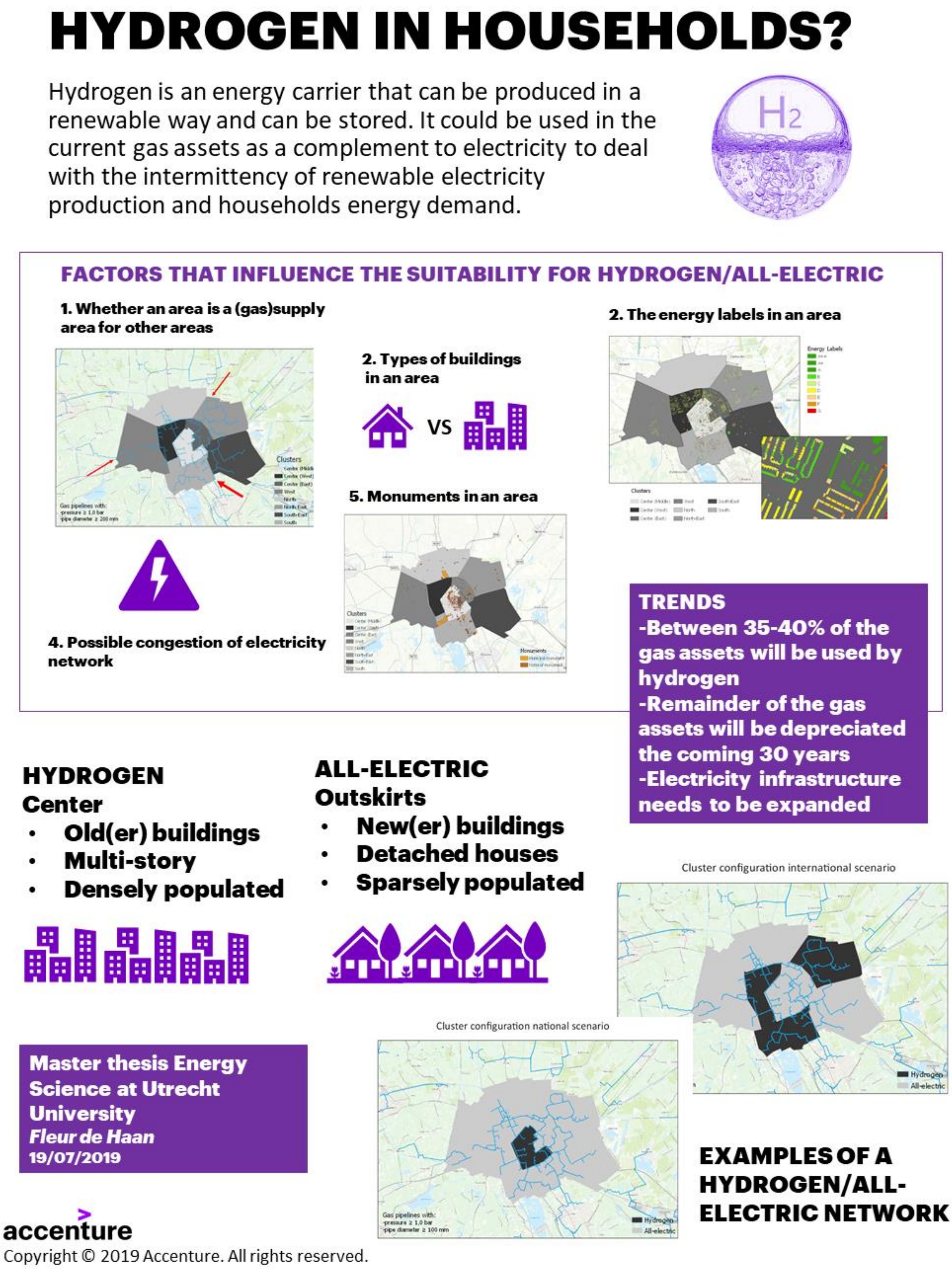
9. Appendix

Appendix A: Infographic



Appendix B: Additional tables and graphical representations of the method

Part 1

In Table 19 the original data derived from the studies done by Gasunie and Netbeheer Nederland is shown that is used as input for the calculation of the hydrogen demand.

Table 19. Energy demand households in 2050 per scenario

(TWh)	Local	National	International
Final energy demand	59	79	84
Electricity	40	32	31
Hydrogen	5	36	27
(Bio)methane	15	12	26

Appendix C: Additional tables and graphical representations of the results

Part 1

Based on Table 19 the values for the Netherlands are converted to the values for Groningen which can be found in *Table 20*. This is done by using the forecasted population size of Groningen as percentage of the total Dutch population size.

Table 20. Energy demand households Groningen in 2050 per scenario

(GWh)	*Local*	*National*	*International*
Final energy demand	697	934	993
Electricity	473	378	366
Hydrogen	236	567	626

Part 2

Figure 16 shows a part of the gas transport map of Gasunie. This map is used as input and to validate the data since it shows the high-pressure pipelines from the TSO after which the DSO will distribute this further at a lower pressure towards the households.

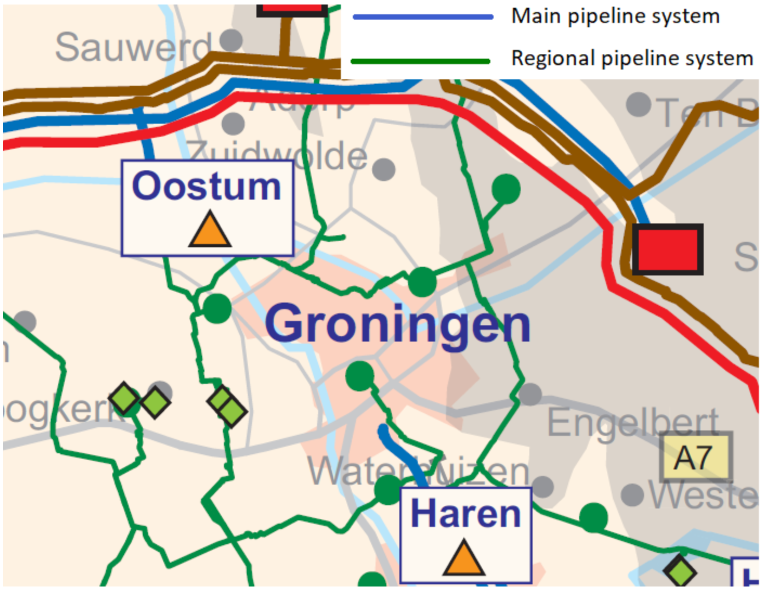


Figure 16. Gas transport system Gasunie (Gasunie Transport Services, 2015)

Table 21 gives more insight in the demographic characteristics of every cluster. This data is used in part 3 to calculate the result of the parameters per area or per number of households to be able to compare the different clusters.

Table 21. Area and number of households per cluster

Cluster	Area (km^2)	Number of households
Center (Middle)	5,5	40920
Center (West)	5,6	18185
Center (East)	3,9	23105
West	16,2	6090

North	15,0	1140
North-East	12,1	14595
South-East	16,1	615
South	10,0	16350

Part 3

Parameter 2 Energy labels per clusters

In Figure 17 the energy labels per cluster are shown. In this representation the labels A++, A+ and A are combined to form one group A. As can be seen, especially South-East has a high percentage of houses with an energy label A and B and the North a high percentage of labels F and G.

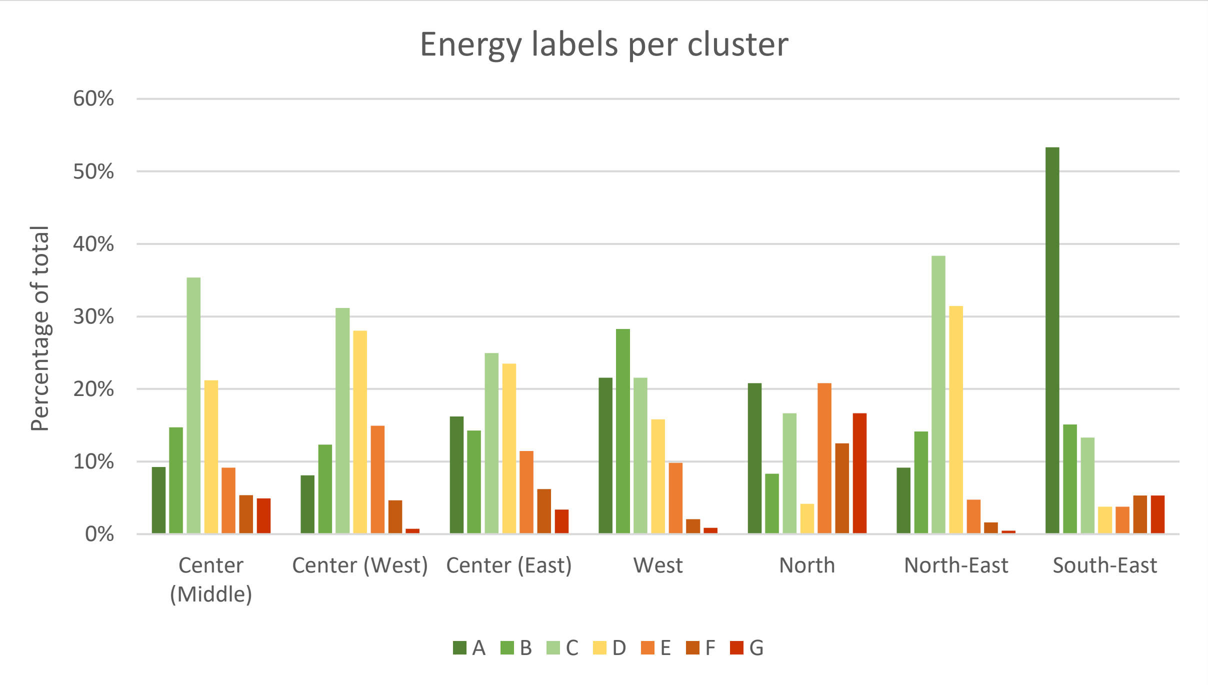


Figure 17. Energy labels per cluster

Parameter 3 Type of buildings (area)

In Table 22 the types of buildings are stated with the corresponding Dutch translation since these are not as straightforward. In addition, the average area according to Agentschap NL and the corresponding score that is given to these types of buildings are shown.

Table 22. Type of buildings with the Dutch translation and the average area

English	Dutch	Average area	Score
Flat apartment	Flat woning	74	1
Gallery flat	Gallerij woning	75	1
Maisonette	Maisonette	85	2
Tenement house	Portiekwoning	68	1
Terraced house	Rijwoning tussen	103	4
Semi-detached house	Twee-onder-een-kap	122	5
Detached house	Vrijstaande woning	150	5

In Figure 18 per cluster the percentage of the type of houses are shown. Some things stand out like the high percentage of detached houses in the North cluster and the low percentage of flat apartments in the West.

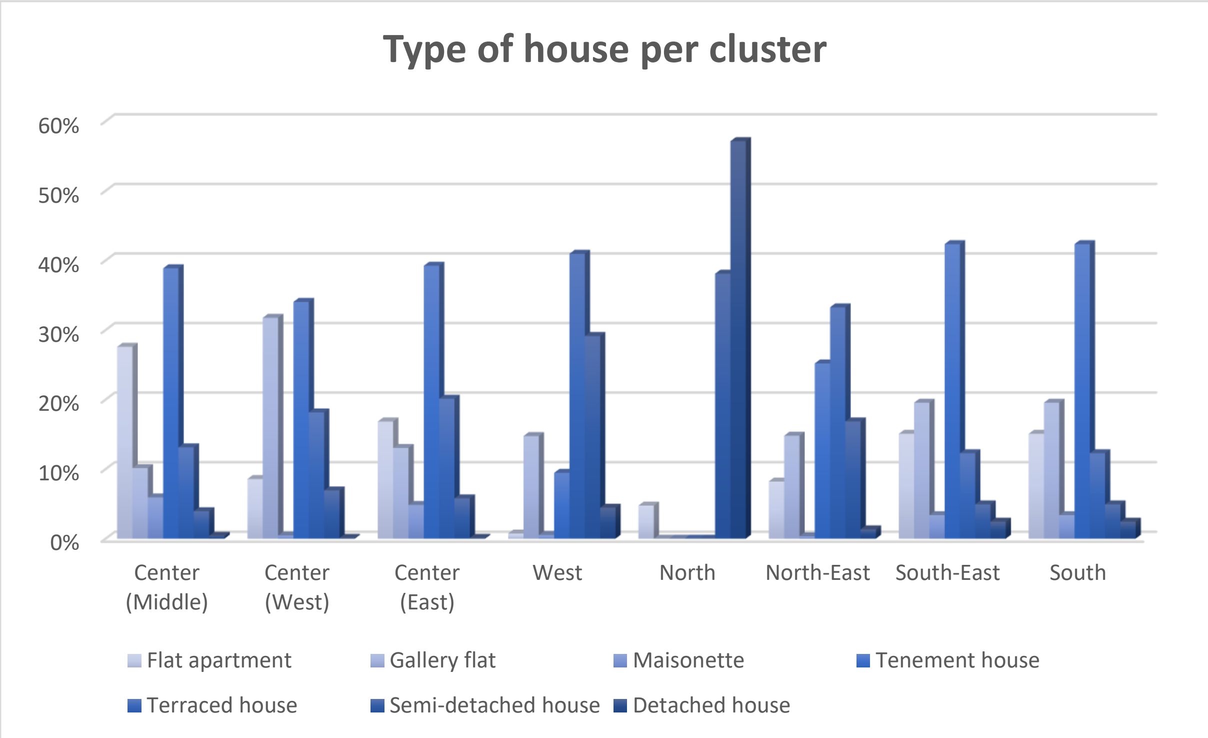


Figure 18. Type of house per cluster

Parameter 4 Monuments

In Figure 19 the percentage of all the houses that is a monument is shown. The North has a high number of monuments. Apparently, the North is not densely populated but a high percentage of the houses that are there are monuments. Since the percentage of cluster North is significantly higher Figure 20 shows the same data without the North cluster. As can be distinguished from this graph, Center (Middle) and Center (East) consist of a relatively high number of monuments.

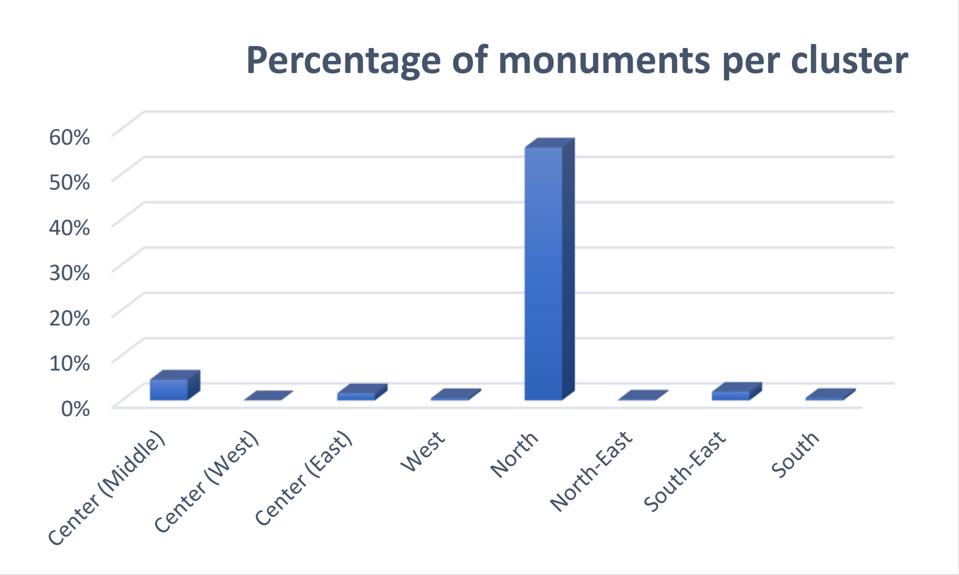


Figure 19. Percentage of houses that is a monument per cluster

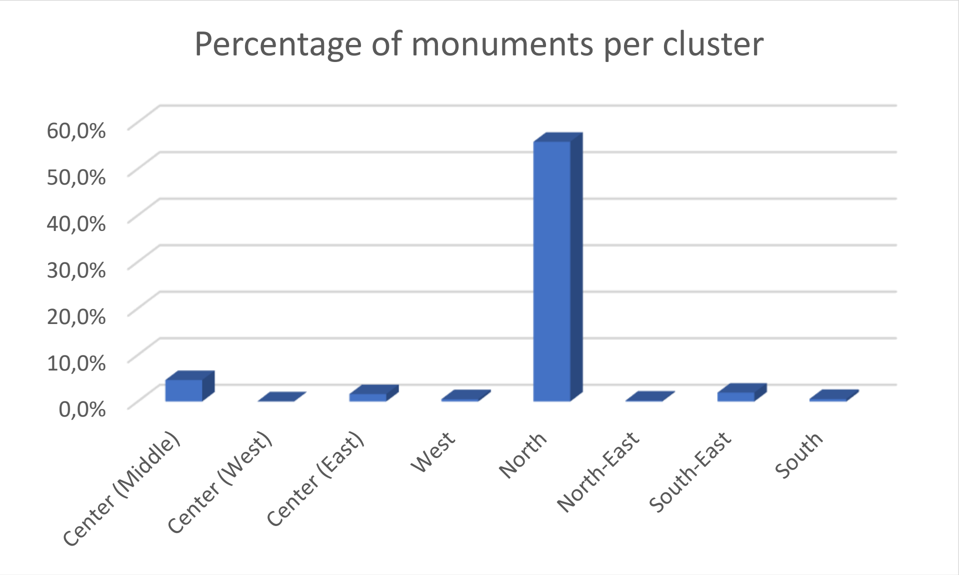


Figure 20. Percentage of houses that is a monument per cluster (without the North cluster)

Parameter 4 Possible congestion of the electricity network

In Figure 21 the average electricity use per cluster is shown. Especially the clusters in the Center have a high energy use per square kilometre.

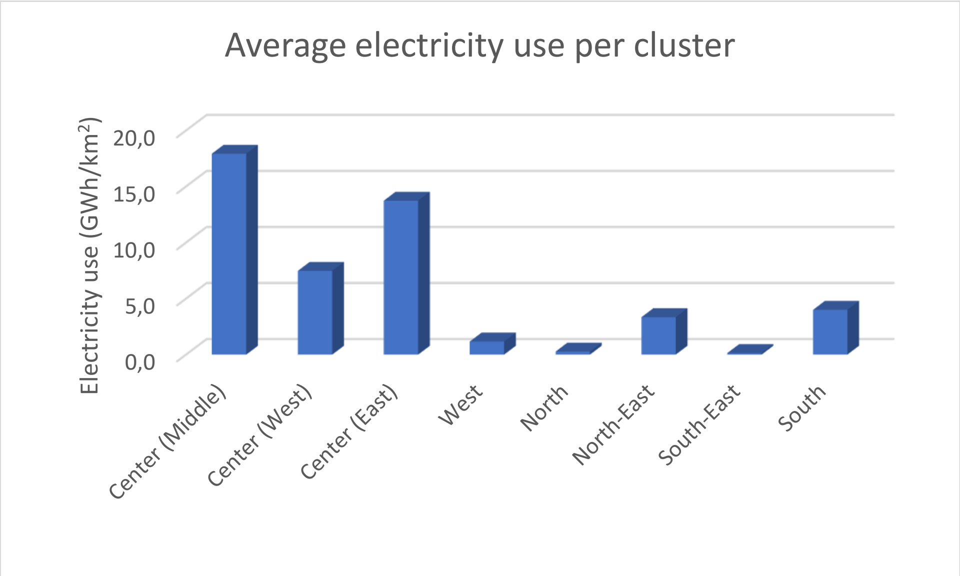


Figure 21. Average electricity use per cluster