Modelling, simulation and analysis of green gas injection into the gas distribution network

Master of Science Thesis

For the degree of Master of Science in Energy & Process Technology at Delft University of Technology

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Abstract

The increase of the average world temperature, as a result of greenhouse gasses, is one of the greatest challenges the world is currently facing and will be facing in the future. One of the many efforts to reduce the increase of carbon dioxide, is to decarbonize the gas network by replacing natural gas with renewable gasses like green gas. Since the current gas network is not always suited for the injection of big green gas volumes, especially during summer periods, the process of decarbonizing the natural gas network requires adjustments of the current functioning of the gas network. Several technical adjustments for obtaining an increased green gas injection capacity exists, although, up to now, the potential green gas injection capacity obtained per solution was not known. Within this study, a dynamic gas network simulation model was developed wherein different gas network function strategies can be explored to obtain the potential green gas injection capacities.

With the developed dynamic gas network simulation model one is capable to implement and simulate different gas distribution network configurations, specify green gas suppliers on the location of choice, simulate different gas demand scenarios and consumer profiles, adjust the city gate station pressure used for simulations of static- and dynamic pressure management, and to model the injection of excess green gas into a storage- and from the storage into the network.

Within this study, the gas distribution network of Northeast Friesland, The Netherlands was analyzed on its green gas injection capacity after applying static pressure management, dynamic pressure management, and a pressure management strategy combined with storage. The gas network of Northeast Friesland was explicitly chosen since currently, green gas injection problems are experienced within this network.

Following the results obtained from the simulations, a city gate station inlet pressure - demand table was defined. Within this table, the total gas demand measured within the network was plotted against the minimum city gate station inlet pressures, while still in compliance with the lower pressure boundary condition. Using this table, the optimal period to statically decrease- and increase the city gate station inlet pressures from 8.3 to 6.5 bar and from 6.5 bar to 8.3 bar, appeared to be respectively 1 May and 1 October. By changing the pressure to 6.5 bar, a safety margin of 1.5 bar was taken into account.

For both static- and dynamic pressure management, green gas injection capacities ranging from 400 to 1600 m^3/h, divided over three green gas suppliers, were analyzed. The results were depicted against the total injectable hours, providing insight in the maximum green gas injection capacity while remaining eligible for the Stimulation of Sustainable Energy Production (SDE+) subsidy. Since with dynamic pressure management the city gate station can inject at lower inlet pressures, dynamic pressure management results in a greater green gas injection capacity. To point out, static pressure management provide 450 m^3/h green gas injection capacity, whereas dynamic pressure management provides 650 m^3/h green gas injection capacity without experiencing any injection problems.

Using the dynamic gas network simulation model, the required size of a storage facility within the gas distribution network, combined with static- or dynamic pressure management, for an average green gas injection capacity of 1600 m/h was determined for the casestudy network. An average green gas injection capacity of 1600 m/h, combined with static pressure management, requires a storage volume of $2.17 \cdot 10^5$ sm^3 whereas the combination of a storage facility and dynamic pressure management requires a storage volume of respectively $1.88 \cdot 10^5$ sm^3. Currently, distribution network operators are legally not allowed to explore their own storage facilities. However, given the requirement

to decarbonize the gas network, the obtained results could be used as an argumentation to obtain permission for the exploitation of a storage facility.

Nomenclature

Abbreviations

CGS City gate station

DAE Differential algebraic equation

DSO Distribution system operator

EU European union

GHG Greenhouse gasses

HTL High pressure transmission lines

KIWA Dutch company specialized in testing, inspection and certification

LNG Liquefied natural gas

MR Metering and regulating stations pressure transmission lines

RTL Regional transmission lines

TSO Transmission system operator

Greek Symbols

ϵ tolerance, -

η efficiency, -

λ gas friction factor, -

ρ density, kg/m^3

Latin Symbols

A area, m^2

c isothermal speed of sound, m/s^2

D demand, m$^3/s$

d diameter, m

dt timestep, s

g gravity, m/s^2

h height, m

k roughness, m

m mass flow rate, kg/s

p pressure, kPa

Q flow rate, m$^3/s$

R	gas constant, J/(molK)
Re	reynolds number, -
T	temperature, °C or K
t	time, s
V	volume, m^3
v	velocity, m/s
Z	compressibility factor, -

Contents

Acknowledgement

Without the following people, this thesis would not be the success it is - and without these people - the process in obtaining this success wouldn't be this enjoyable;

For their academic assistance I want to thank my supervisors Paulien Herder and Petra Heijnen and for both his academic input and in company guidance, I want to thank Iman Pishbin.

W.B. Sprangers,
Delft, University of Technology

"The gas is greener on the other side."
– *W.B. Sprangers*

1. Introduction

1.1 Background

1.1.1 Global warming

Global warming, the increase of the average world temperature as a result of greenhouse gasses, is one of the greatest challenges the world is facing for the future. When greenhouse gasses build up in the atmosphere, it allows sunlight to heat up the earth's surface but traps the heat as it radiates back into space causing the earth's temperature to increase. According (Lenssen et al., 2019), between 1906 and 2005 the global average surface temperature rose 0.6 to 0.9 °C where over the past 50 years the rate of temperature increase has doubled, shown in figure 1.1.

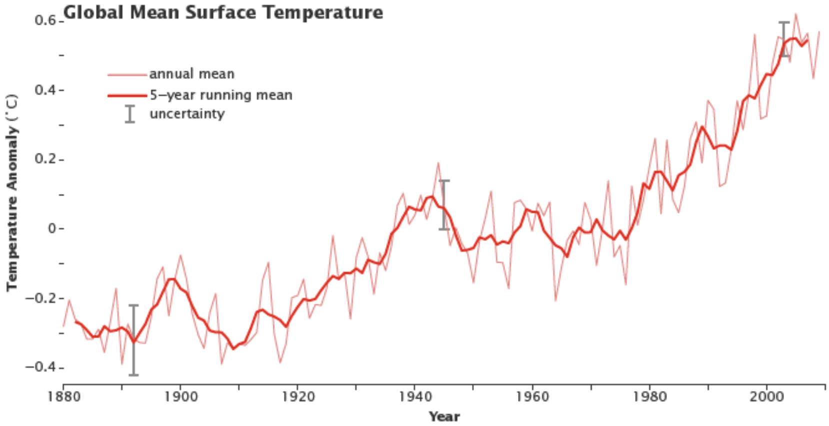

Figure 1.1: Global mean surface temperature measured from 1880 to 2000. NASA figure adapted from (Lenssen et al., 2019)

1.1.2 Energy transition goals

What scientists concern is that over the past 250 years, humans are artificially raising the concentration of greenhouse gasses at an ever increasing rate. One of the main greenhouse gasses is CO_2 and according data from (Laštovička et al., 2006), since the industrial revolution began in about 1750, carbon dioxide (CO_2) levels have increased with nearly 38 percent as of 2009. To act against this increase of carbon dioxide levels, the European Union (EU) has set cutting greenhouse gasses in order to prevent climate changes, as a key priority. Key targets for the year 2030 are a minimum reduction of 40% greenhouse gas emissions compared with 1990 and at least 32% of the total energy consumed originating of renewable energy. As a long term goal, by 2050 the EU aims to cut its emissions by 80-95% compared to 1990 (Commission, 2012).

1.1.3 Biogas as a renewable gas

In order to achieve the by the European Union defined targets, and to avoid dangerous climate changes, significant and concerted transitions in our energy sources are required. Next to solar and wind energy, renewable gas is expected to be one of the key players within future energy systems. Biogas, biomethane, green hydrogen and synthetic natural gas are all examples of renewable gasses.

Figure 1.2 depicts the process where organic waste is processed into green gas (biomethane). Anaerobic digestion is the process of converting organic waste into biogas energy. For biogas, different sources of production lead to different specific compositions. Typically, biogas is composed of 60% methane (CH_4), 35% carbon dioxide (CO_2) and 5% other compositions such as water and nitrogen (resp. H_2 and N_2)[1]. By cleaning and upgrading the biogas (removing the CO_2), biogas can be used in the form of biomethane - a renewable substitute for natural gas.

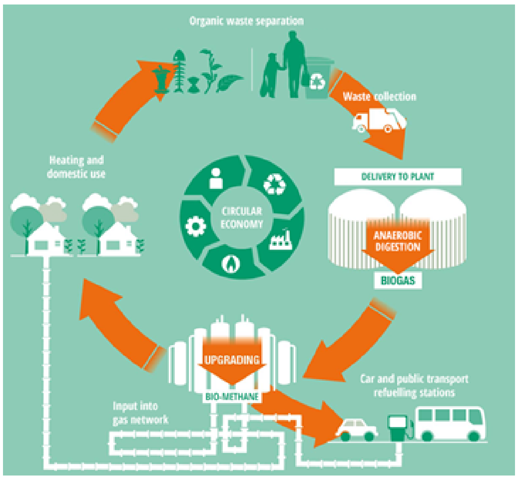

Figure 1.2: Illustration of a circular economy in which organic waste is converted to green gas and used for heating and transport purposes (Group, 2019)

Gas is of great importance within the Dutch energy system. In 2018, the overall energy consumption within The Netherlands stood at 3100 PJ (petajoules) wherein gas consumption accounted for over 40% of the total energy consumed (1285 PJ)[2]. Therefore, decarbonizing the gas network (increase the percentage of green gas) could drastically reduce the amount of GHG emissions and contribute in achieving the energy transition goals.

Decarbonizing the gas network is a much discussed topic. To emphasize, in a letter from the Dutch Minister of Economic Affairs and Climate Policy, it was plead to expand the green gas production and the necessity to adjust the current functioning of the gas network was highlighted (Wiebes, 2020). The necessity to adjust the current functioning of the gas network is mentioned in several other studies as well (Weidenaar et al., 2011) (Dumont et al., 2018).

1.2 Problem definition

The current gas network is used to transport natural gas from a source, through transmission lines, into the country. Transmission lines are high- and medium pressure pipelines (resp. >67 and 40 bar) in which natural gas is transported to large industrial consumers or to the city gate station. At the city gate station (CGS), the pressure is reduced (<8 bar) and injected into the gas distribution network. The gas distribution network is, compared to transmission pipelines, characterized by lower pressures, smaller gas flows and often a meshed grid. Via the distribution network, gas is provided to final consumers such as small industry and households.

Whereas the supply of natural gas is controlled by the city gate station, biogas production is continuous, decentralized, and usually injected into the lower pressure gas network. Given that biogas

[1]http://www.biogas-renewable-energy.info/biogas_composition.html Last: 2 August 2019
[2]https://www.cbs.nl/en-gb/news/2019/16/energy-consumption-down-in-2018 Last: 1 August 2019

production is a continuous process, green gas suppliers require the ability to continuously inject green gas into the network. However, since the gas demand is not always as high as the green gas supply, especially during summer months, the injection of big green gas volumes is not always possible and green gas injection problems occur. During periods when the green gas supply exceeds the demand, the network is filled to its maximum allowable pressure whereas the excess green gas is flared in order to not let the produced green gas accumulate and disrupt the process. This supply and demand mismatch will later be discussed in more detail (section 1.2.3).

1.2.1 Subsidy

Besides green gas flaring does not contribute in obtaining the climate goals, for the green gas supplier, green gas flaring has another negative consequence. To elaborate, in order to balance the economic exploitation of green gas production, a green gas supplier is dependent on the "Stimulation of Sustainable Energy Production" (SDE+) subsidy. Briefly, SDE+ is an operating subsidy that compensates for the difference in production costs and market price in order to boost the production of renewable energies (Lensink & Cleijne, 2016). However, to be eligible for the SDE+ subsidy, a green gas supplier is obligated to inject green gas into the network for a minimum of 8000 hours per year. Should this requirement not be met, no subsidy is obtained resulting in a nonviable operation for the green gas supplier.

1.2.2 Current approach

Since the viability of a green gas supplier is dependent on the SDE+ subsidy, the possibility to inject for a minimum of 8000 hours per year should be guaranteed. This guarantee is provided by the distribution network operator, the company that owns and operates the lower pressure gas networks. We discuss the method Stedin applies to guarantee the ability to inject for 8000 hours per year. Stedin is a Dutch gas distribution network operator for which this study is conducted.

To ensure the ability for green gas suppliers to obtain the requirement of 8000 hours green gas injection per year, Stedin provides a maximum hourly green gas injection capacity equal to the summerlow gas demand (Pishbin, 2020). The summerlow gas demand is defined by the lowest hourly gas demand, measured during the months May to October. To elaborate, figure 1.3 depicts the gas demand of a week in June for which the summerlow gas demand measures 750 m^3/h. Following this example, a maximum total green gas injection capacity of 750 m^3/h would be provided by the distribution network operator (Stedin).

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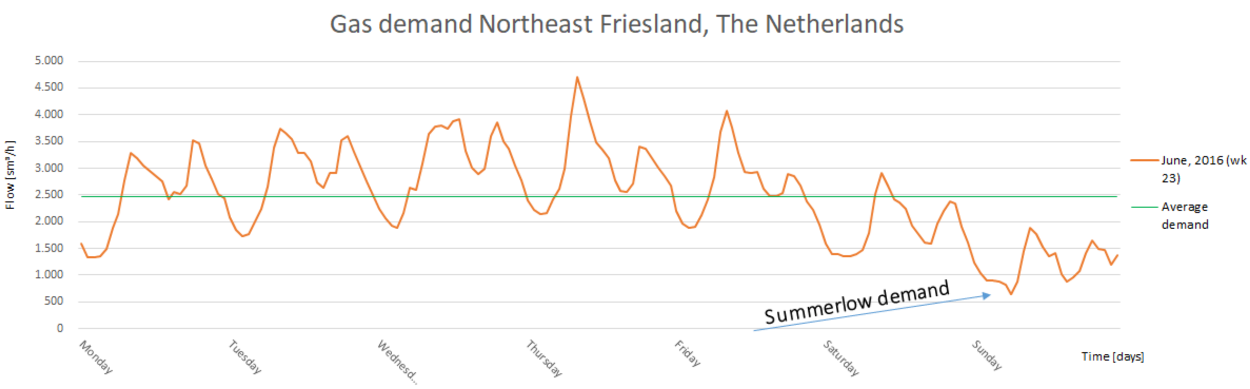


Figure 1.3: Gas demand profile Northeast Friesland, The Netherlands

1.2.3 Supply and demand mismatch

An analysis of the gas demand profile of Northeast Friesland is performed to get a better grasp on the variation in demand and supply, and to further illustrate the problem. The gas network of Northeast Friesland is used since this network is operated by Stedin, and currently has open enquiries for the injection of green gas to which Stedin has no answer whether the network has the capacity to support these amounts. For the analysis, gas demand data of the year 2016 was provided by Stedin. Since from 2016 to now, no noticeable (gas demand) changes were performed in the network, the data is valid for usage.

Figure 1.4 depicts the hourly gas demand of Northeast Friesland, in the year 2016. The differences in gas demand per month are clearly visible. Roughly, the gas demand decreases from January to May, is the lowest between May and October, and increases from October to January. Based on the figure, green gas injection problems occur between May and October.

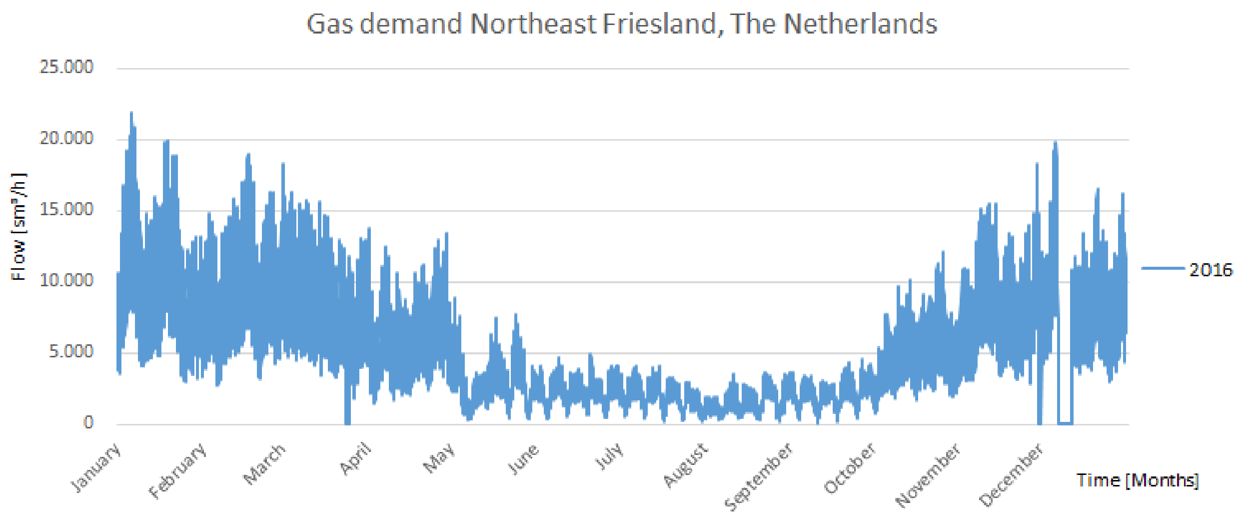


Figure 1.4: Gas demand profile Northeast Friesland, The Netherlands

In figure 1.5, the hourly gas demand of the months February and June are shown. Again, the difference in gas demand per month is clearly observable. Also, a large variation in the minimum and maximum gas demand during a day is seen, which implies the difference in day and night consumption. This variation in minimum and maximum gas demand per day will later appear to be useful in balancing the green gas supply and demand mismatch, providing an increased green gas injection capacity, section 2.2.1

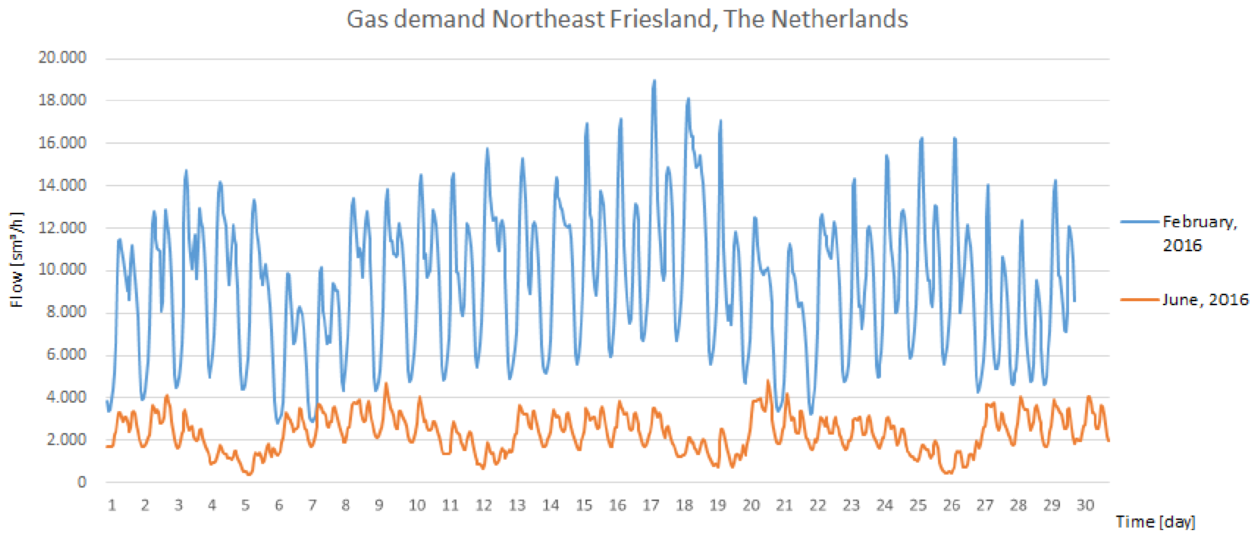


Figure 1.5: Gas demand profile Northeast Friesland, The Netherlands

By observing both the hourly gas demand during a year, and for the months February and June, it is concluded that green gas injection problems occur between May and October.

1.2.4 Solutions

With the ongoing increasing production of renewable gasses, distribution network operators face the challenge of managing a network with increasing supply. Therefore, finding solutions to increase the green gas injection capacity of the gas distribution network is mandatory to maintain and increase the development of renewable gas usage within The Netherlands. Although there are some known technical solutions to increase the green gas injection capacity, it is unclear which solution- or which combination of solutions should be used under which circumstances. Figure 1.6 depicts the technical green gas injection capacity increasing solutions. The different solutions are discussed in more detail in section 2.2.

1. Directly into the high pressure network
2. On site storage facility
3. Connection to local big gas consumers
4. Green gas booster in the distribution network
5. Static pressure management
6. Dynamic pressure management
7. Connect different distribution networks

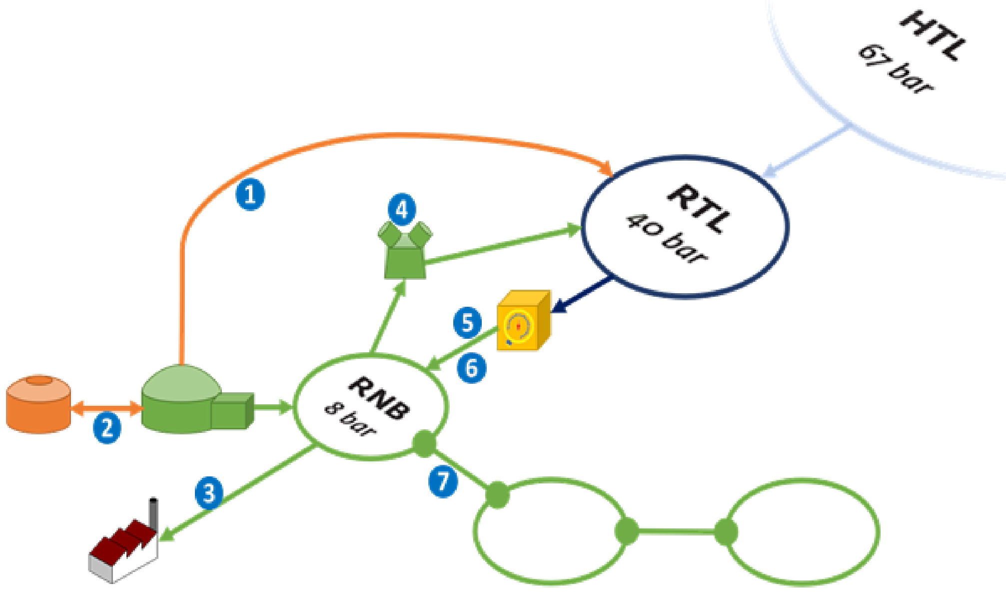


Figure 1.6: Green gas injection capacity increasing solutions (Stedin, 2020)

1.3 Research objective

Several technical solutions to provide an increased green gas injection capacity are known. However, currently, the distribution network operator has no knowledge on the specific increase per solution, nor when to apply which solution. Therefore, this study aims to obtain a substantiated answer on the potential green gas capacity increase within the gas distribution network, as a consequence of applying capacity increasing solutions- or a combination of solutions.

The research objective is achieved by the development of a dynamic gas network simulation model. With this model, the gas distribution network can be analyzed for different hourly gas consumption profiles, different green gas injection capacities, and different capacity increasing solutions from which the green gas injection capacity is obtained.

1.4 Research questions

In order to achieve the objective of this study, research questions are defined. The main question of this research is:

What is the potential green gas injection capacity of different solutions -or a combination of solutions- within the gas distribution network?

To answer the research question, a mathematical representation of the physical behaviour of the gas distribution network (dynamic gas network simulation model) is required. For the development and realization of this model, the following sub questions are established:

- *What are the crucial network characteristics within the gas distribution network?*
- *How to develop a mathematical model which reflects the physical behaviour of the gas distribution network?*

- *How to describe the crucial network characteristics within the model?*
- *What are the potential green gas injection capacities for the different solutions -or a combination of solutions- for the casestudy network in Northeast Friesland?*

1.5 Methodology

1.5.1 Literature

The first part of this study involves a literature study. First, knowledge on the current functioning of the Dutch gas network is obtained, and several green gas injection capacity increasing strategies are discussed. Provided with this knowledge, similar studies wherein green gas injection problems are encountered are referenced, and both static- and dynamic gas network simulation models are analyzed to see how the objective of the study can be supported.

1.5.2 Dynamic gas network modelling

The modelling accounts for the biggest part of this study. A dynamic gas network simulation model is modeled using the open source software Python. The dynamic gas network simulation model provides the possibility to analyse the gas distribution network, and explore different green gas injection capacity increasing strategies.

1.5.3 Validation and simulation

The model is validated according two methods. In the first method, the outcomes obtained from the model are compared with results obtained from literature. For the second method, an abstracted version of the gas distribution network as located in Northeast Friesland, The Netherlands (Dokkum-Hallum) is implemented into the model, of which the results are compared with results obtained from the commercialized steady state gas network calculation program Irene Pro.

Several simulations are performed to observe the potential green gas injection capacity of the casestudy network in Northeast Friesland, while applying different green gas injection capacity increasing solutions. Provided with the results obtained from the simulations, the different green gas injection capacity increasing solutions are discussed and compared, and possible recommendations for future work are given.

1.6 Scope

The focus of the study is to obtain a substantiated answer on the green gas injection capacity within the gas distribution network, as a consequence of capacity increasing solutions- or a combination of solutions. Therefore, the study solely focuses on capacity expansion and thus, solutions wherein e.g. a modulated biogas production is assumed, are not within the scope of this study. Also, for this study, solely the 8 bar gas distribution network is considered.

2. System description

Within this chapter, the literature survey is highlighted.

First, to get a grasp on the functioning of the gas network, the Dutch gas network is reviewed. Second, existing capacity creating solutions and studies wherein these solutions are analyzed are discussed and last, different ways of modeling a gas network are discussed to determine the modelling approach for the current study.

2.1 The Dutch gas network

Gas is supplied to industry and households according a top-down method shown in figure 2.1. The supply of natural gas starts at pressure levels above 67 bar where gas flows in so called high pressure transmission lines (HTL). Via metering and regulating stations (M&R) connected to the high pressure transmission lines, the gas pressure is reduced to 40 bar and fed into the regional transmission lines (RTL). Connected to the RTL are city gate stations (CGSs), city gate stations reduce the pressure from 40 bar to pressure levels ranging from 4 to 8 bar and supply the distribution network with gas. The gas distribution network consist of a high- and low pressure distribution network and distributes gas to both industry and households.

Within this section, the different pressure level pipelines, as the responsible parties for each part of the network are discussed.

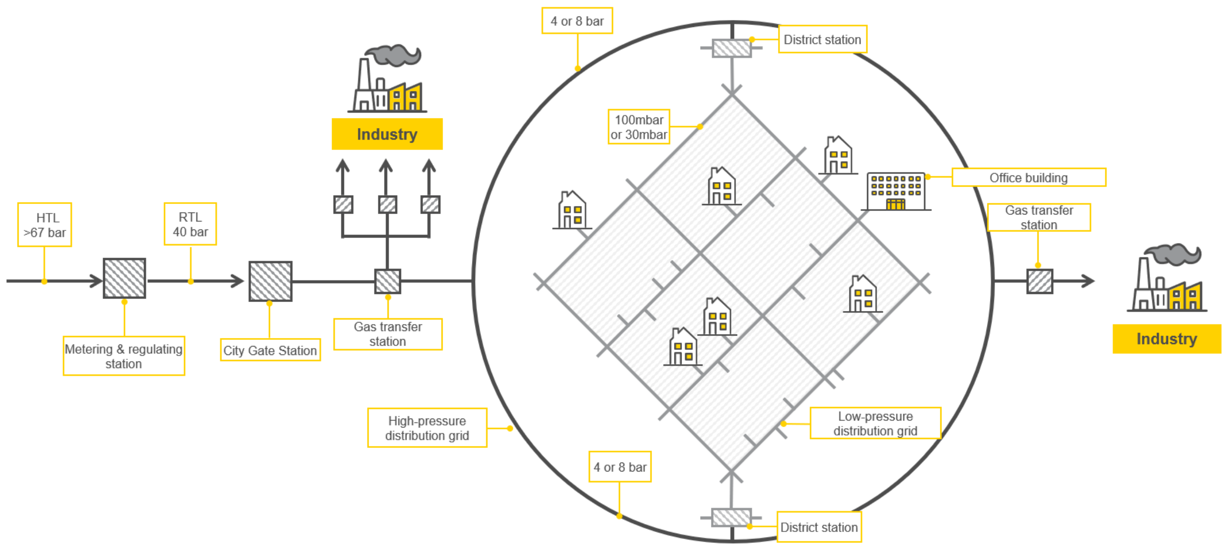


Figure 2.1: Top-down schematic of the Dutch gas grid (Stedin, 2020)

2.1.1 High pressure transmission lines

Within The Netherlands, high pressure transmission lines are divided in two categories; one for the transport of high calorific gas and one for the transport of Groningen gas. Both are connected via mixing stations enabling the mixing of high calorific gas and nitrogen with the Groningen gas. Besides mixing stations, the HTL contain compressors enabling the transport of gas.

Gas is fed into the high pressure transmission lines via LNG terminals or via entrypoints providing imported gas, and gas produced within The Netherlands. Exitpoints of the HTL are either transferpoints to gas terminals, other countries or metering and regulating stations which reduce the gas pressure to 40 bar and provide gas to the regional transmission lines for usage within the country (Weidenaar et al., 2011).

2.1.2 Regional transmission lines

Via metering and regulation stations the gas pressure is reduced to 40 bar and fed into the RTL network. The regional transmission lines transport the gas further into the country and in some cases directly supply gas to big industrial consumers. Generally, the gas from the regional transmission lines is supplied to city gate stations where the pressure is reduced to 8 (or 4) bar and fed into the gas distribution network.

2.1.3 Distribution network

The gas distribution network is divided into multiple gas pressure levels- the high pressure distribution network ranges from 8 to 4 bar and the low pressure distribution network ranges from 4 bar to 30 millibar, figure 2.1.

The high pressure gas distribution network transports the gas over longer distances and via a district station, which reduces the pressure to 100 or 30 mbar, gas is fed into the lower pressure distribution network. From both the high and low pressure network gas is extracted and supplied to (small) industries and household.

2.1.4 Responsibilities

The different gas networks, resp. the high pressure transmission lines, regional transmission lines and the gas distribution network are controlled by different parties. Both the high pressure and regional transmission lines are controlled by a transmission system operator (TSO) which for The Netherlands is the GasUnie, a public company. For the gas distribution network, within The Netherlands, there are six parties who are responsible for their part of the gas distribution network. These parties are called distribution network operators (DNO).

2.2 Gas balancing

As mentioned in section 2.1.3, as a consequence of the increasing demand for renewable energies, the gas distribution network is bound to see some changes in the foreseen future. One of these changes, which already is being employed, is the decentralized injection of green gas. However, because of the varying gas demand and a continuous green gas injection, decentralized green gas injection often lead to capacity problems within the gas distribution network.

In this section, four green gas injection capacity creating solutions - resp. linepack flexibility, static pressure management, dynamic pressure management, and a storage facility are discussed, and different studies which analyze the capacity creating solutions are mentioned.

2.2.1 Linepack flexibility

A physical property of gas is the ability to expand and compress making it possible to store variable amounts of gas within a network, without changing the network volume, linepack flexibility. In figure

2.2 the linepack flexibility principle is schematically shown - measuring the same pipe volume, an increased gas pressure results in an higher amount of gas molecules. Since a distribution network operator (Stedin) is able to vary the gas pressure within the gas distribution network, linepack flexibility can be used to balance the green gas supply and demand mismatch.

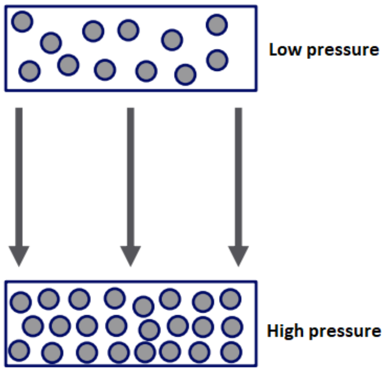


Figure 2.2: Schematic of linepack flexibility

The pressure within the gas distribution network is changed by reducing- or increasing the city gate station inlet pressure. Since gas naturally flows from higher to lower pressures, reducing the city gate station inlet pressure while maintaining a higher green gas injection pressure provide the green gas supplier with a storage potential defined by the difference in injecting pressures, the network volume, and a chosen reference condition (Keyaerts et al., 2011).

Storage potential
The potential storage capacity within the gas distribution network is dependent on the geometry, and both the minimum- and maximum operating pressure of the network. The maximum operating pressure is a fixed value, determined by the material characteristics, and the minimum operating pressure is a variable depended on, among others, the transport distance, to compensate for friction to ensure enough pressure at each point within the network. Figure 2.3 gives an illustration of the linepack flexibility concept. Within the figure, the storage potential for an adjusted inlet pressure is visualized by the area p_a, p_b, p_d and p_c while ensuring the defined pressure boundary conditions.

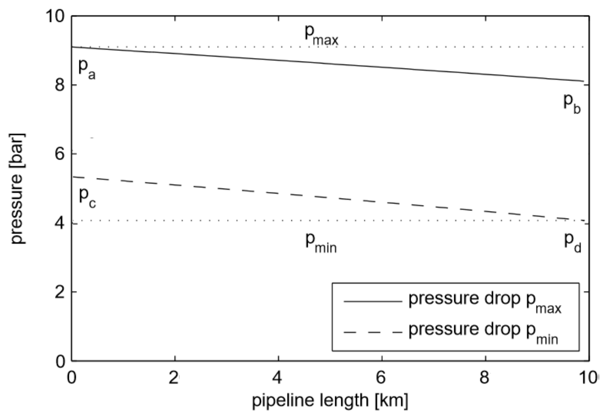


Figure 2.3: Line-pack flexibility and pressure development: the storage potential is visualized by the area p_a p_b p_d p_c with p_{max} and p_{min} as the upper- and lower pressure boundary conditions (Keyaerts et al., 2011) (modified)

In figure 2.4, different approaches of linepack flexibility and different methods of how this principle can be used to match a variation in demand and supply are shown. The figure was found in a study of (Keyaerts et al., 2011) which analyzes the gas balancing rules and regulation of the high pressure transmission pipelines. The HTL is different than the regional distribution network though, the principles shown remain applicable. The examples in figure 2.4 assume a constant gas demand over the course of a day and vary the time of injection in order to illustrate the change in linepack.

Figure 2.4a (early injection) matches to figure 2.4b. Here, a linepack buffer is created by injecting more gas than the actual demand. In figure 2.4c (late injection), the linepack shown in figure 2.4d is firstly being used, after which at a certain moment in time injection takes place and the buffer is refilled.

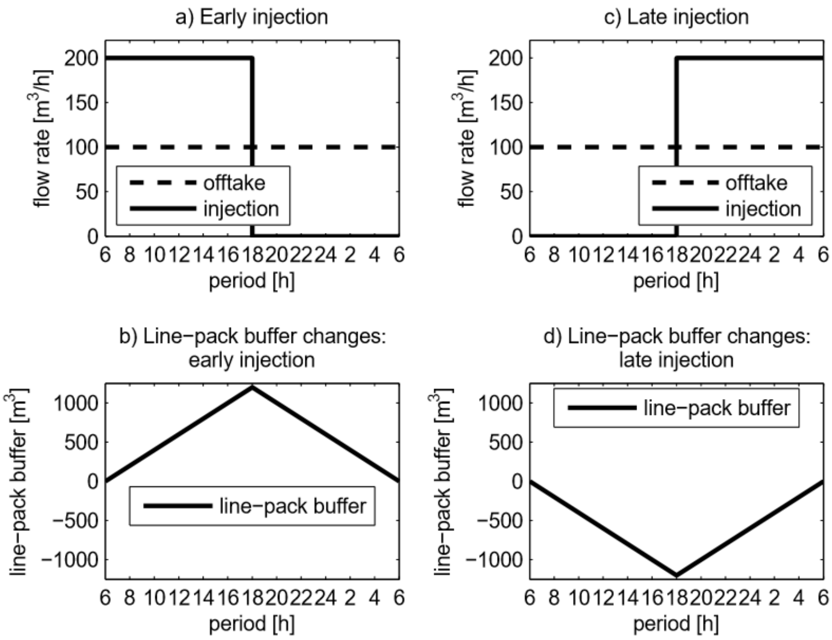


Figure 2.4: Different approaches of line-pack flexibility used to match hourly variation in demand and supply (Keyaerts et al., 2011)

A basic principle of storage is that one can only withdraw what has been injected before. For the case of linepack flexibility this means that the distribution network can serve as a buffer during periods when the green gas supply exceeds the demand (e.g. during summer nights) and can be emptied when the demand exceeds the supply. Controlling the gas distribution network pressure is called pressure management, distinction is made between static- and dynamic pressure management.

Static pressure management

Static pressure management is the concept of statically adjusting the city gate station inlet pressure to in- and decrease the pressure within the gas distribution network. Static pressure management is controlled by both the DNO and the TSO. If an adjustment of the city gate station inlet pressure is required, the DNO contacts the TSO in order to manually in- or decrease the city gate station inlet pressure. By decreasing the CGS inlet pressure, assuming a constant gas demand, the pressure within the gas distribution network decreases resulting in a green gas storage potential due to the minimum- and maximum allowable pressure within the gas network. To elaborate, when the network operates between 3.5 and 8 bar, and we fill the network to 3.5 bar, the ability to add an extra 4.5 bar to the network is obtained.

In Northeast Friesland, Stedin successfully applied the concept of static pressure management to obtain more green gas injection capacity within the gas distribution network. In this operating area, during summer, the city gate station inlet pressure is decreased from 8.3 to 7.5 bar, and during fall, to ensure the supply of gas throughout the network, the pressure is increased from 7.5 to 8.3 bar. As a result of the lack of sufficient calculation tools, no exact numbers regarding the increase of capacity for the gas distribution network in Northeast-Friesland can be given.

To the best of our knowledge, no literature study on static pressure management within the gas distribution network has been done. Reasonably, this can be explained by the rather simple concept of static pressure management.

Dynamic pressure management
Dynamic pressure management has the same objective as static pressure management though, contrary to static pressure management, dynamic pressure management is an automated process. With the use of pressure sensors, located within the gas distribution network, the city gate station can inject gas with minimum pressure levels while ensuring the lower limit pressure condition within the network.

In a non-public document of KIWA, commissioned by Stedin, the results of a dynamic pressure management study are listed (Laat, 2016). For this study, a by Stedin operated 8 bar gas distribution network located in Utrecht, The Netherlands was used as a pilot in which the following four strategies were tested

1. Automatically stop injecting green gas into the distribution grid when a predefined pressure is reached.
2. Reduction of green gas injection per green gas supplier as a function of the pressure.
3. Pressure controlled gas injection by the CGS.
4. Gas injection as a function of the outside temperature.

For the current study, strategy 3 - pressure controlled injection by the CGS - is the most relevant since this strategy focuses on finding a balance between the green gas storage capacity and the reliability of the network. To clarify, green gas storage capacity is obtained by a reduced CGS inlet pressure and reliability is obtained by ensuring enough pressure within the entire network, and thus an higher CGS inlet pressure. Therefore, a balance between the two should be found. The pilot was tested successfully which is promising for further research for deployment in the Dutch gas distribution network. However, no values regarding the increased capacity for green gas injection were given.

2.2.2 Gas storage

A gas storage facility can be used to store gas surpluses obtained during periods when the production exceeds the demand, which later can be injected during periods of higher demand. Essentially, linepack flexibility is a type of storage. Since distribution network operators are, according the law, not allowed to maintain gas storage facilities (Pishbin, 2020), the gas storage facilities as described in this section refer to storage facilities managed by -and located at- the green gas production plant.

(Green) gas can be stored both above and underground in gaseous or liquefied state. Gaseous green gas can be stored in e.g. cylindrical bottles and spherical tanks. Liquefied gas is stored in cylindrical cryogenic bottles and cryogenic tanks. For underground storage, all the above ground storage techniques can be be used with the extra possibility to use depleted oil and gas reservoirs or salt caverns (Budzianowski & Brodacka, 2017).

Underground storage
In general, (natural) underground storage facilities such as salt caverns have very large storage capacities and are used for large scale applications requiring long term storage. Given that distribution network operators are not allowed to exploit there own storage facilities, and for a green gas supplier it is not reasonable to exploit such large storage facilities, this study focuses on smaller scale applications with short term storage (daily variation in gas demand). Therefore, underground storage facilities are not within the scope of this study and will further not be mentioned within detail.

Tank storage
Tank storage can be distinguished in low, medium, and high pressure storage. Low pressure green gas storage can be done by the use of green gas storage bags. Green gas storage bags are used for small scale (on site) storage to balance the daily variations in green gas supply and gas demand. Within the green gas storage bags, gas is stored at atmospheric pressure.

Compressed (green) gas can be stored in both cylindrical, spherical, and pipe tanks. Where for spherical tanks the gas is generally stored at pressures below 10 bar (medium pressure), pipe tanks can maintain pressures up to 100 bar (high pressure). To point out what the storage pressure means for the volume green gas that can be stored in the different storage facilities, equation (2.1) is used. By increasing the storage pressure from 10 to 100 bar, leaving the storage volume unchanged, up to 10 times of the green gas volume can be stored - giving pipe tanks up to 10 times the storage capacity of spherical tanks, using the same storage volume. Basically, the storage pressure is a trade-off between storage capacity per volume and costs. For example, if we want to transport the stored gas, high pressure storage could favor low pressure storage since more gas can be transported even though compressor costs are higher.

$$p_1 \cdot V_1 = p_2 \cdot V_2 \tag{2.1}$$

Where p_1 - Standard pressure, V_1 - Volume expressed in normal cubic meter, p_2 - Variable pressure to meet the equation, V_2 - Variable volume to meet the equation.

Gas storage conclusion
Since distribution network operators are not allowed to exploit their own storage facilities within the gas distribution network, and various possibilities to store green gas exist, for this study it was decided not to focus on specific storage methods but rather on the storage size required to be able to inject specific green gas injection capacities. To elaborate, the required size of a storage facility to obtain a certain green gas injection capacity will be obtained in standard cubic meters (atmospheric pressure). Providing this number, a distribution network operator can -in consultation with the green gas supplier- determine which storage facility suits the purpose the best.

2.2.3 Gas network coupling

Besides the concept of linepack flexibility, and the use of storage facilities, the coupling of multiple gas distribution networks can be done to obtain an increased green gas injection capacity. The coupling of multiple gas distribution networks causes the total network volume to increase, and thus, the storage potential, section 2.2.1. Another benefit of the coupling of multiple gas distribution networks is an increased total gas demand which result in an higher green gas injection capacity. in figure 2.5, a schematic of the coupling of multiple gas distribution networks is shown.

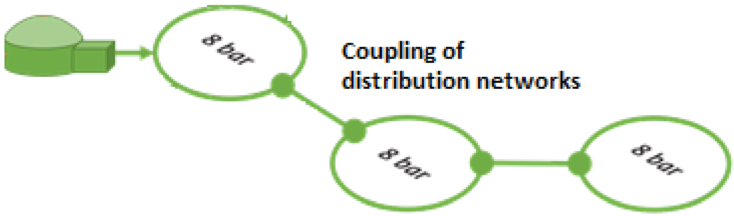


Figure 2.5: Schematic of the coupling of different gas distribution networks

Gas network coupling conclusion

In an advice report, written by Netbeheer Nederland, it was stated that regions with significant green gas potential require grid adjustments in the form of grid connection(s) combined with strategically placed boosters (section 2.2.4) in order to create more green gas injection capacity and be able to transport green gas from the distribution network into the RTL (Engberts et al., 2018). No specific regions- or calculations were given.

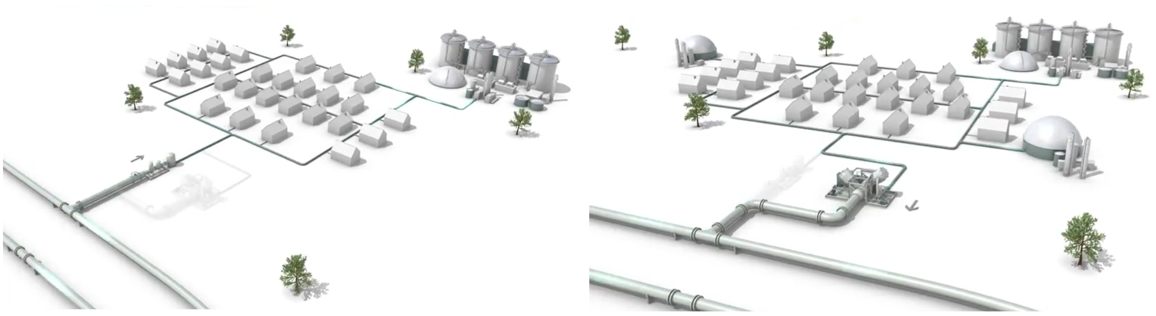
The coupling of multiple gas distribution networks certainly offers potential for an increased green gas injection capacity though, given the case dependency of the solution, it was decided for the current study not to focus on the coupling of multiple gas distribution networks. However, it will come apparent that, with the model build, the possibility to analyse the coupling of multiple gas distribution networks exists.

2.2.4 Green gas booster

As a solution to match green gas supply and demand within the gas distribution network, literature often refers to a green gas booster (Engberts et al., 2018). A green gas booster is a large compressor providing a connection between the regional green gas supply, and the national gas demand resp. gas distribution network and the regional transmission lines. By exploiting a green gas booster, green gas (surpluses) can be compressed to pressure levels above 40 bar and injected into the regional transmission lines. Since the national gas demand has enough sales options at national level, green gas can be injected all year around (PWC, 2012) without the occurrence of injection problems.

Two different booster station setups can be thought off. One in which a direct connection between the green gas supplier, the gas distribution network, and the regional transmission lines is established, and another in which the green gas booster station is located directly within the gas distribution network providing all potential green gas suppliers connected to the same distribution network access to the booster station. Both setups serve the same purpose - enable green gas suppliers to inject green gas into the gas distribution network.

Figure 2.6 gives an illustration of a green gas booster station connected to the gas distribution network and the regional transmission lines. The green gas booster as shown in figure 2.6b compresses the gas surplus of the entire gas distribution network, providing multiple green gas suppliers to have access to the booster.



(a) No gas surplus - gas booster bypassed (b) Gas surplus - gas booster active

Figure 2.6: Green gas booster providing a connection between the regional green gas supply and the national gas demand (Attero, 2019)

Green gas booster conclusion
Reflecting on the current study, it was decided to not explicitly analyse the green gas booster station. Reason for not explicitly analysing the green gas booster within the current study is because of the capacity obtainable with a green gas booster. In essence, by exploiting a green gas booster within the gas distribution network, a connection to the national gas demand is made. Provided this connection, it is not the question whether there is enough green gas injection capacity, but rather what the size of the green gas booster station should be.

2.2.5 Conclusion

Following this section, linepack flexibility can be used to balance the green gas supply and demand mismatch. The storage potential obtained with linepack flexibility is a variable depended on the geometry of the gas distribution network and the difference in the minimum and maximum allowable pipeline pressures. Where linepack storage is obtained via and from the existing gas distribution network, a storage facility (underground storage/storage tank) is external and does not contribute to the main function of the gas distribution network. By coupling of multiple gas distribution networks, a greater total network volume is obtained providing a greater linepack flexibility. Next to the linepack managing strategies, a green gas booster exist. By exploiting a green gas booster, green gas can be injected into the regional transmission lines resulting in 'unlimited' green gas injection capacity. The green gas injection capacity increasing solutions, analysed within the current study, are summarized in table 2.1

Table 2.1: Green gas injection capacity increasing solutions analysed within the current study

Green gas injection capacity solution
Static pressure management
Dynamic pressure management
Storage facility (size provided in sm^3)

2.3 Gas network modelling

The currently available gas network software IrenePro, used within Stedin, is limited to static calculations and no time based gas consumption profiles (e.g. hourly/daily) can be implemented. Within static calculations, the gas flow in- equals the gas flow out ($\frac{\partial Q}{\partial x} = 0$) and thus e.g. the increase of injection capacity achieved by linepack flexibility cannot be analyzed. Therefore, in order to determine the increased injection capacity achieved by one of the capacity increasing solutions (section 2.2), a dynamic gas network model should be made.

Within this section, different gas network modelling approaches are analyzed and the requirements for the model are elaborated to determine the most suited method for the current study.

2.3.1 Model functions

Since the objective of the study is to provide a substantiated answer on the increase of green gas injection capacity within the Dutch gas distribution network, as a consequence of capacity increasing solutions- or a combination of solutions, the main functions of the model are to support the analysis and to determine the green gas injection capacity increase of the different solutions.

Within the previous sections, different capacity increasing solutions with different characteristic were discussed. As an example; where the characteristics of pressure management are to in- or decrease the CGS inlet pressures, the storage solutions make use of linepack managing strategies. Therefore, in order to simulate these characteristics, the model should be able to support the following functions.

- Allow inlet pressure modulation at the city gate station(s).
- Allow exploration of linepack managing strategies.
- Allow variable green gas injection in both the network and storage facilities.

2.3.2 Modelling approaches

The different type of gas network models can be divided into static- and dynamic resp. steady and unsteady state models. For both the static- and dynamic modelling approach, various different solving methods are mentioned within literature (Ekhtiari, Dassios, Liu, & Syron, 2019b). Below, the differences between static- and dynamic modelling are elaborated and different studies in which the modelling approaches are being used are discussed.

Steady state modelling
Within literature, steady state modelling is frequently used where the pressure and the flow rate at the in- and outlet of the pipelines are assumed constant in time (Ekhtiari et al., 2019b). In a study of (Abeysekera, Wu, Jenkins, & Rees, 2016), a steady state analysis method was developed for gas networks with distributed injection of alternative gasses. The main objective of this study is to show the impact of utilizing multiple gas sources on pressure distribution and gas quality within the network. In another study of Ekhtiari (Ekhtiari, Dassios, Liu, & Syron, 2019a), a novel method to solve the gas flow equations within a gas network under steady state conditions is shown. The main objective of this study was to provide a new and different solving method for gas networks. Other studies for which the steady state modelling approach is used focus on e.g., pipeline optimization (Ríos-Mercado, Wu, Scott, & Boyd, 2002), operational and investment costs optimization (Üster & Dilaveroğlu, 2014) and fuel cost optimization for the steady state gas pipeline networks (Wu, Rios-Mercado, Boyd, & Scott, 2000).

Steady state modelling is, as found within literature, often used for simulating gas networks and is suited for various problems and analyses. However, since steady state modelling is based on equilibrium conditions, the research objective cannot be obtained. Within steady state modelling, for the simulation of gas networks, the assumption is a constant in- and outlet flow. Therefore, linepack flexibility and storage facilities (2.2) cannot be simulated with this method causing the steady state method to be inadequate for the current study.

Dynamic modelling

The combination of dynamic modelling and the simulation of gas networks is a relative new topic. Reason for this being a relative new topic is the shift from fossil to renewable energies and the consequences (variable compositions of gasses, distributed injection) this shift has for the gas network systems. In a study of (Guandalini, Colbertaldo, & Campanari, 2017) a dynamic model was developed to simulate the non-steady-state operation with variable gas compositions and the effects on flow and pressure drop within the network compared to the reference case of natural gas. By doing so, an indication of the maximum allowed fractions renewable gasses (hydrogen, methane) was found. In a study performed by Farzaneh (Farzaneh-Gord & Rahbari, 2018), a dynamic gas network model was made to analyze the response of a gas distribution pipeline to ambient temperature variation. Both models were non public - the study of (Guandalini et al., 2017) was performed as a PhD study whereas the study done by (Farzaneh-Gord & Rahbari, 2018) was commissioned by an Iranian gas company which provided financial support for the research. Therefore, there was no possibility to use the models within the current study.

In a study of Kwabena Addo Pambour (Pambour, Bolado-Lavin, & Dijkema, 2016) a dynamic model was developed in order to simulate the security of supply scenarios in integrated gas and electricity networks. The main goal of this study was to analyze how the integration of gas and electricity networks effect the both systems and how to approach potential bottlenecks. In essence, the study of Kwabena Addo Pambour largely connects with the current study. However, in the study of Pambour the focus was on high pressure transmission lines and the consequences of potential gas supply failures where the focus of the current study is on the gas distribution network and the effect a variable gas demand has on the injection of green gas. Also, since the model as build by Pambour is commercialized, and not open acces, their is no possibility wherein a part of the model is used and adjusted to the requirements of the current study.

Contrary to steady state modelling, with dynamic modelling, the imbalance between gas supply and gas demand resulting in fluctuations in linepack can be described.

Therefore, since currently no open access dynamic gas network simulation tool which could answer the research objective exists, and thus in order to achieve the goal of the study, a dynamic gas network simulation model is developed.

A more in depth description on the mathematics and the modelling approach is found in chapter 3.

3. Dynamic simulation model

In this chapter, the modelling approach of the dynamic gas network simulation model is discussed and benchmarked with different models found in literature.

First, the fundamental gas flow equations - and the assumptions made in order to simplify the gas flow equations - are described. Second, the solving method combined with an algorithm for solving the model is given and last, the solving method is benchmarked against different solutions obtained from literature in order to validate the obtained values.

3.1 Gas dynamics in pipelines

In a typical gas distribution network the main components are pipelines. The dynamics of gas transport along pipes is described by the Euler equation representing the laws of conservation of mass, conservation of momentum and conservation of energy. The Euler equations are nonlinear and derived from the Navier-Stokes equations. For a more extensive elaboration of the Navier-Stokes equations see (Sheng, 2019).

In this study, as thoroughly discussed in literature describing the gas dynamics in pipelines (Qiu, Grundel, Stoll, & Benner, 2018), the gas temperature is assumed constant throughout the gas network causing the energy equation to be neglected which result in the isothermal Euler equations. Isothermal gas flow - and more assumptions - are discussed in section 3.1.1.

3.1.1 Isothermal Euler equations

Within this study, the flow of a gas in a gas network is described by a combination of the isothermal Euler equations and the real gas law. By combining the isothermal Euler equations with the real gas law, the pressure is coupled with the density of the gas. The conservation of mass and momentum are described by resp. Eq. (3.1) and (3.2) and the real gas law is described by Eq. (3.3).

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial x} = 0 \tag{3.1}$$

$$\underbrace{\frac{\partial (\rho v)}{\partial t}}_{\text{inertia}} + \underbrace{\frac{\partial p}{\partial x}}_{\text{pressure}} + \underbrace{\frac{\partial (\rho v^2)}{\partial x}}_{\text{convection}} + \underbrace{\frac{\lambda \rho v \mid v \mid}{2d}}_{\text{shear}} + \underbrace{\rho g \frac{\partial h}{\partial x}}_{\text{gravity}} = 0 \tag{3.2}$$

$$\frac{p}{\rho} = ZRT \tag{3.3}$$

Since the set of partial differential equations (Carrier & Pearson, 2014) describing the gas flow in pipes are rather complex, simplification assumptions are done. Simplification assumptions regarding the modelling of gas flow within a gas network is thoroughly discussed within literature (Qiu et al., 2018) (Herrán-González, De La Cruz, De Andrés-Toro, & Risco-Martín, 2009). For the current study, the following simplification assumptions are done.

- **Isothermal flow:** Temperature variations throughout the gas network are assumed to have negligible effects on the dynamic behaviour of the gas flow. Therefore, the gas temperature is assumed constant in time and space. By assuming a constant gas temperature, the energy equation becomes redundant and can be neglected (isothermal Euler equations).

- **Creeping flow:** Due to the rather small gas velocities in the pipelines (<20m/s) the convective term is, compared to the other terms in the momentum equation, negligible. In (Herrán-González et al., 2009) the convective term was studied to be of the order 10^{-3} compared to the change in pressure in space.
- **Slow changes in boundary conditions:** During normal operation, boundary conditions concerning pressure and flow change gradually over time causing the inertia term to be neglected.
- **Homogeneous elevation:** The model as proposed in the current study is used for the Dutch distribution network. Therefore, homogeneous elevation is assumed causing the gravity term to be neglected.
- **Constant compressibility:** According to the compressibility factor calculation method, developed by (KIWA, 2014), the compressibility factor Z of natural gas within the range of 3.5 - 8.5 bar differs with less than 0.8%. Therefore, a constant compressibility factor is assumed.

Next to the simplification assumptions, the following relation for the isothermal speed of sound c is obtained from the state equation, Eq. (3.4).

$$\frac{p}{\rho} = c^2 = ZRT \tag{3.4}$$

By applying the above assumptions, the relation for the isothermal speed of sound c and the relation for the flow rate Q, the density at standard conditions ρ_n and the mass flow rate m, Eq. (3.5).

$$m = \rho_n Q = \rho v A \tag{3.5}$$

The set of partial differential equations describing the gas flow in a pipe are simplified and rewritten to the following set of equations, Eq. (3.6) and (3.7).

$$\frac{\partial p}{\partial t} = -\frac{\rho_n c^2}{A}\frac{\partial Q}{\partial x} \tag{3.6}$$

$$\frac{\partial p}{\partial x} = -\frac{\lambda \rho_n^2 c^2}{2\eta_e^2 D A^2 p} \mid Q \mid Q \tag{3.7}$$

Where p - pressure of the gas, ρ_n - normal gas density, c - speed of sound, A - area of the pipe, Q - gas flow, λ - gas friction factor, D - diameter of the pipe, η_e - efficiency factor.

3.1.2 Continuity equation

The continuity equation, Eq. (3.6) describes the imbalance between in- and outflow at the boundaries of a pipeline section. When analyzing the terms in the equation, it is found that the change in pressure over time is described by the amount of gas stored within a specific pipe section. This storage of gas within a specific pipe section is called linepack, section 2.2.1.

3.1.3 Continuum equation

With the continuum equation, Eq. (3.7) the pressure drop along the pipeline as a result of frictional forces acting opposite to the flow direction, is described. The frictional force term is derived from the Darcy-Weisbach equation (Haktanır & Ardıçlıoğlu, 2004). The Darcy-Weisbach equation is an empirical equation which relates the pressure loss due to friction along a given pipe length to the average velocity of the fluid flow through the pipeline.

Friction factor

Various methods for approximating the friction factor λ are given in (Brkić, 2018), (Koch, Hiller, Pfetsch, & Schewe, 2015) and (Benner et al., 2018). According (Benner et al., 2018), the Hofer equation, Eq. (3.8) is of sufficient accuracy for transient gas network simulations. The Hofer equation is an explicit variant of the well known Colebrook-White formula.

$$\lambda = (-2log_{10}(\frac{4.518}{Re}log_{10}\frac{Re}{7} + \frac{k}{3.71D}))^{-2} \tag{3.8}$$

Within this study, the friction factor is approximated by the Nikuradse approximation, Eq. (3.9). The Nikuradse approximation results from the Hofer formula for $Re \to \infty$, which is elaborated in (Bekkering, Broekhuis, van Gemert, & Hengeveld, 2013)

$$\lambda = (-2log_{10}(\frac{k}{3.71D}))^{-2} \tag{3.9}$$

The friction factor λ as obtained from Eq. (3.9) refers to a straight pipe. Therefore, to account for curvatures and the form of the pipeline, an efficiency factor η_e is introduced. According to literature, most experts recommend using a value of 0.9 to 0.92 for the pipeline efficiency factor (Farshad, Choate, Winters, & Garber, 2017). The effective friction factor λ_e is defined by Eq. (3.10).

$$\sqrt{\frac{1}{\lambda_e}} = \eta_e\sqrt{\frac{1}{\lambda}} \tag{3.10}$$

3.2 Solving method

For solving partial differential equations, three widely used numerical methods exist: finite element method, finite difference method and finite volume method. All methods represent a systematic numerical method for solving partial differential equations, with each method having its own pros and cons.

The isothermal Euler equations are conservation laws which are generally solved by the finite volume- or the finite difference method. The biggest difference in both solving methods is the accuracy of the solution. According (Vinokur, 1986) the solution of a finite difference method is more accurate than the finite volume solution which is due to the flexibility in mesh size. Therefore, within this study, the finite difference method is used for solving the isothermal Euler equations.

3.2.1 Network description

To mathematically describe the gas network, nodes and directed edges (elements of the graph theory) are used. Within the graph theory, a directed edge refers to an element with an inlet,- outlet and a flow direction. Since for this study, other than pipes, no components such as valves or compressors are being used, the directed edges represent the different pipe sections within the network.

A connection between two or more pipes is described by nodes, giving each pipe in the network at least one common in- or outlet node with another pipe within the network. Besides serving as a junction of two different pipe sections, a node can also serve as a demand, supply or a storage node. Figure 3.1 gives an overview of the different nodes within the network. At demand nodes, gas is extracted from the network. Examples of demand nodes are district stations (connection to the lower distribution network), factories and households. At supply nodes, gas is injected into the system. A supply node could be a city gate stations or a green gas supplier. A storage node is (because of legal reasons) less common within the current distribution network and represents gas storage facilities. In a storage node, gas can potentially be injected or extracted. At last, the junction node is to describe a change in e.g., pipe diameter or a connection of 3 or more pipes.

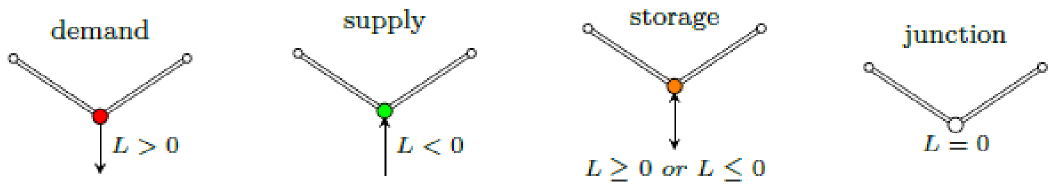


Figure 3.1: Characteristic of the different network nodes

In order to mathematically combine the directed edges and nodes, and describe the topology of the gas network, the incidence matrix A is used, figure 3.2. The incidence matrix A is a nxm matrix with n the number of nodes and m the number of pipes. The incidence matrix is, according the following definitions, filled by zeros, ones and negative ones .

- +1: node i is the outlet of pipe j
- -1: node i is the inlet of pipe j
- 0: node i and pipe j are not connected

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
3	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
4	0	0	0	1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	-1	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	-1	-1	1	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	-1	0	-1	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	-1	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

Figure 3.2: Incidence matrix of a Dutch gas distribution network in Northeast Friesland

3.2.2 Discretization

In order to solve the isothermal Euler equations, the equations need to be discretized. Discretization is the process of transferring a continuous function into one which is merely solved at discretized points (Neill & Hashemi, 2018). One can apply the implicit- or explicit finite difference method for solving the set of partial differential equations with as a difference; for explicit solutions, parameters are calculated based on previous (time, space) levels where in the implicit scheme parameters are dependent on another at the same time level. Generally, implicit methods are harder to use but provide the user with more stable answers. Therefore, taking into account both accuracy and stability, the isothermal Euler equations are solved using the implicit finite difference method.

Discretized continuity equation
The continuity equation Eq. (3.6) describes the relation in pressure and the amount of gas stored within the pipe (linepack). When an imbalance between in- and outflow Q occurs, both the pressure and linepack change. The in- and outlet of a pipe section (directed edge) are described by mathematical nodes, the pressure referred to with the continuity equation describes the pressure within a node, figure 3.3.

For each node, a nodal volume V_i is determined. Figure 3.3 gives an example on how to calculate the nodal volume. As seen within the figure, the volumes of the pipeline sections are equally divided over the system and the nodal volumes are calculated according the following equation, Eq. (3.11).

$$V_i = \frac{\pi}{8} \sum_{j=1}^{k} D_{i,j}^2 \Delta x_{i,j} \tag{3.11}$$

Where V_i - Volume of node i, $D_{i,j}$ - Diameter of pipe segment (i, j), $x_{i,j}$ - Length of pipe segment (i, j).

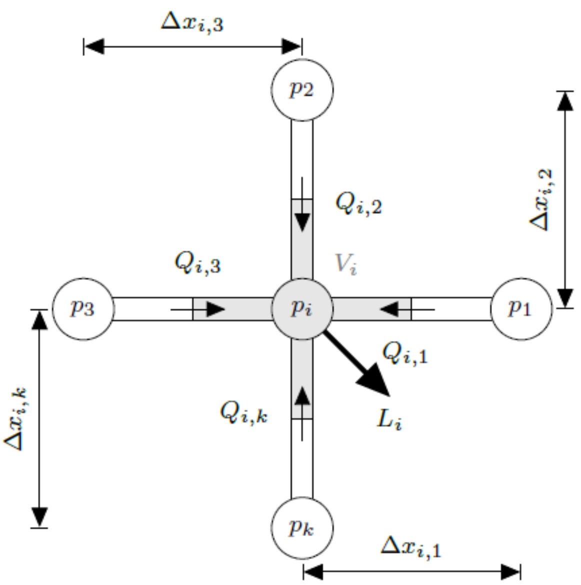


Figure 3.3: Mass conservation applied to a nodal control volume within a gas network (Pambour et al., 2016)

For the continuity equation, for each time dependent variable, an implicit time integration step ($\Delta t = t_{n+1}$ - t_n) is performed. The equation is ordered in terms of known variables and boundary conditions at time t_n and t_{n+1} at the right hand side and unknown variables at time t_{n+1} on the left hand side. The following finite difference matrix equation is obtained for the system, Eq. (3.12).

$$\frac{V_i}{\rho_n c^2 \Delta t} p^{(k,n+1)} - \text{A}Q^{(k,n+1)} = \frac{V_i}{\rho_n c^2 \Delta t} p^{(k,n)} - L^{(k,n+1)} \tag{3.12}$$

Where A - incidence matrix, L - Vector of nodal loads, ρ_n - Density at normal conditions, c - Speed of sound.

Discretized momentum equation
The momentum equation, Eq. (3.7) is solved by averaging the flow rate Q and the friction factor λ over the pipe section with length Δx = l and the following discretized equation is defined, Eq. (3.13).

$$P^{(k+1,n+1)} - P^{(k,n+1)} - R_f \mid Q^{(k+1,n+1)} \mid Q^{(k+1,n+1)} = 0 \tag{3.13}$$

Where $P^{(k+1,n+1)}$ - Squared pressure at the pipe outlet, $P^{(k,n+1)}$ - Squared pressure at the pipe inlet, R_f - Pipe resistance coefficient, $Q^{(k+1,n+1)}$ - Average pipe flow

3.2.3 Algorithm

Figure 3.4 shows the flow chart of the algorithm used for solving the transient gas network. The Newton-Raphson method is used to solve the set of equations, Eq. (3.13) (3.12), numerically and iteratively for each time step t_{n+1}. First an initial approximation, using the previous time step- or the initial condition is used to determine the solution for the set of equations at t_n. the solution is then compared against a predefined tolerance ($\epsilon = 10^{-2}$, ..., 10^{-7}) for which the solution should be less in order to proceed to a next time step t_{n+1}. When the maximum number of iterations (k_{max}) is reached and no solution is found for the system, the tolerance may be changed or the maximum iterations may be increased. If still no solution is found, the system may not be able to converge. When $t_n = t_{max}$ and for each time step t_n a converged solution is found, the system is solved successfully.

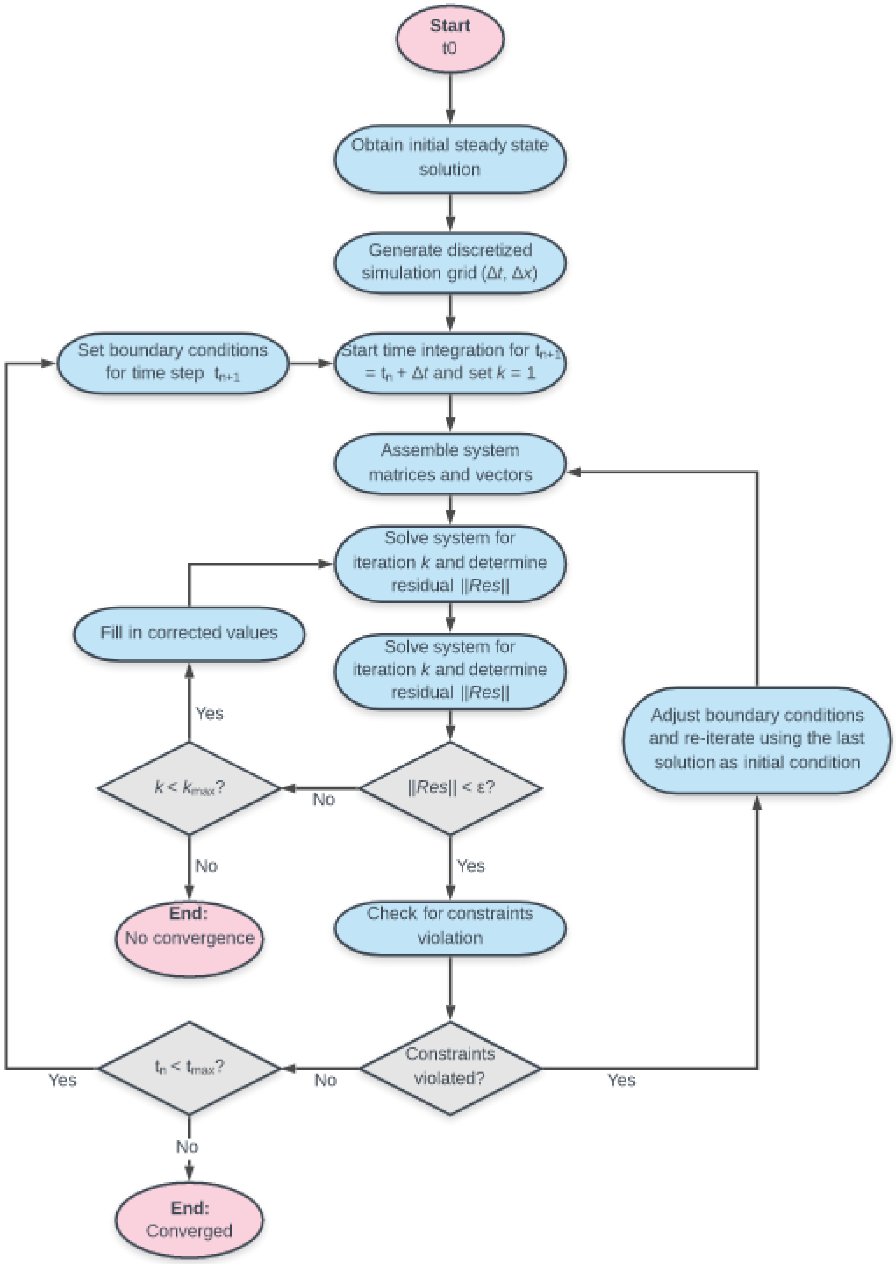


Figure 3.4: Algorithm used for solving the dynamic gas distribution network model

3.3 Model benchmarking

Within this section, the proposed model is benchmarked against solutions obtained from literature to verify whether the answers determined by the model are reliable. The model is benchmarked against the well-known triangular network (Osiadacz, 1987) and a bigger, more complicated transportation network containing 6 nodes and 7 pipes, the diamond network (Benner et al., 2018).

Both the triangular and the diamond gas transportation network are high pressure networks of resp. 50 and 80 bar. Given this knowledge a certain error is expected since the compressibility factor of natural gas within the 50 - 80 bar region differs from the compressibility factor of the low pressure region, and a constant compressibility factor was assumed for the model proposed within this study, see 3.1.1

3.3.1 Triangular Network

The within this study proposed model is used to solve the gas network shown in figure 3.5. The outcomes are compared with solutions from the following papers (Osiadacz, 1987), (Ke & Ti, 2000) and (Pambour et al., 2016).

The triangular network consist of three pipelines, a supply node (node 1) and two demand nodes (node 2 and 3). At the supply node, gas is injected into the system and the demand nodes extract gas from the system. The pipe data is found in table 3.1. The simulation and gas properties are copied from (Pambour et al., 2016) in order to compare the outcomes. The simulation properties are found in table 3.2, for the gas properties see (Pambour et al., 2016).

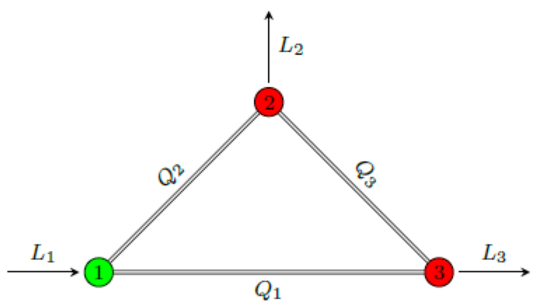


Figure 3.5: Topology of the triangular network

Table 3.1: Input parameters transient model

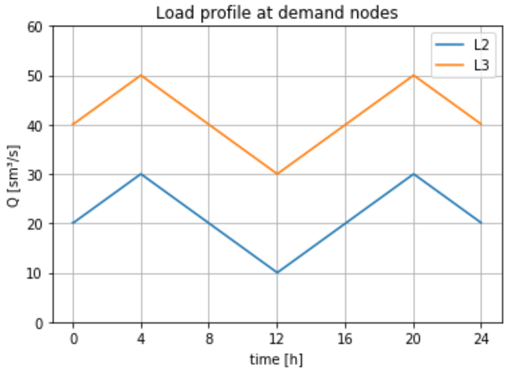
Pipe -	Diameter [m]	Length [m]	Roughness [mm]
1	0.6	80000	0.012
2	0.6	80000	0.012
3	0.6	80000	0.012

Contrary to (Ke & Ti, 2000) and (Osiadacz, 1987) the pipe sections are discretized in only 1 pipe segment (directed edge between two nodes) resulting in less computational time and storage. For the simulation, a time step dt = 180s with a total simulation time t_n = 24h is used. The same residual tolerance as used within (Pambour et al., 2016) was used.

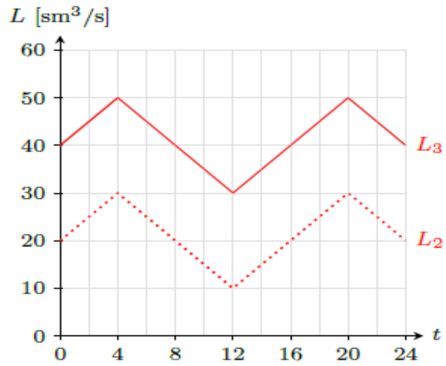
Table 3.2: Simulation parameters for the transient simulation of the triangular gas network

Parameter	Symbol	Value	Unit
Grid segments per pipe	-	1	[-]
Time step	dt	180	[s]
Total simulation time	t_n	24	[h]
Residual tolerance	ϵ	10^{-4}	[-]

Load profiles
The given load profiles (boundary conditions) of the demand nodes 2 and 3 are found in figure 3.6. In 3.6a the load profile of the model as described in this study is shown and in 3.6b the load profile as found in literature is shown. Since this is an input condition, no deviation is expected here.



(a) Load profile at the demand nodes 2 and 3

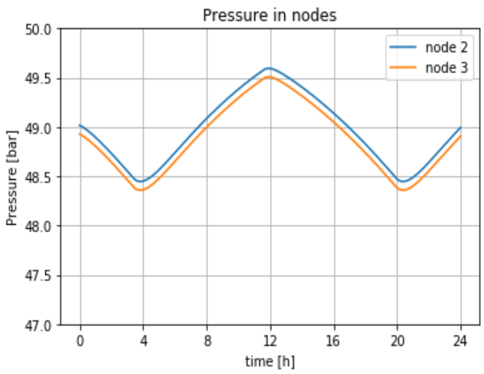


(b) Load profile at the demand nodes 2 and 3 (Pambour et al., 2016)

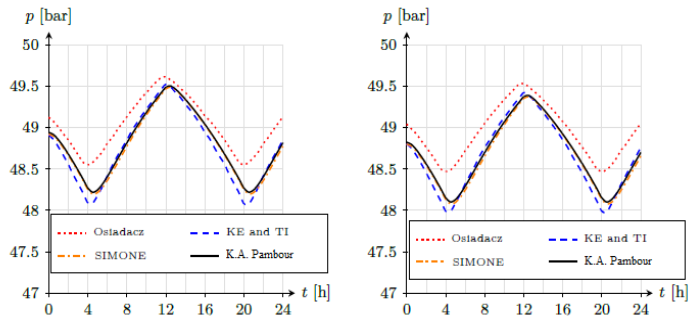
Figure 3.6: Boundary conditions for the transient simulation of the triangular network

Pressure profiles
Figure 3.7a shows the computed pressure profiles at node 2 and 3. In figure 3.7b, the pressure profiles of the different models as found within literature are shown and table 3.3 show the exact pressures of node 2 and 3 at simulation hours 4 and 20

As expected, and according to physics, the pressure at the demand nodes decrease with an increasing nodal load and increase with a decreasing nodal load. Compared with the results obtained from literature the computed results are the most similar with the results obtained by (Osiadacz, 1987). The maximum deviation is found with the results of (Keyaerts et al., 2011), giving a deviation below 1% at both simulation hour 4 and 20.



(a) Computed pressure profiles at node 2 and 3



(b) Pressure profiles at node 2 and 3 (Pambour et al., 2016)

Figure 3.7: a) The computed pressure profiles at node 2 and 3 b) Pressure profiles found within literature

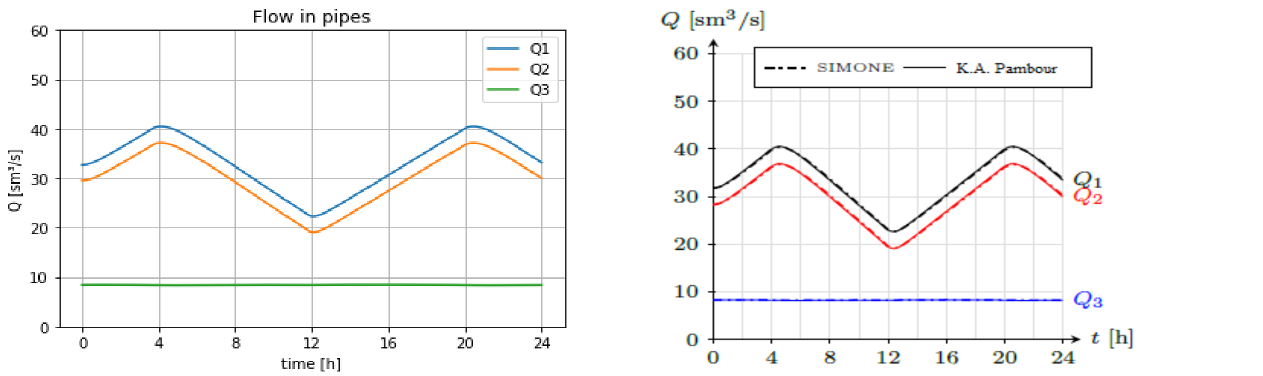
Table 3.3: Triangular network pressure of node 2 and 3 at simulation hours 4 and 20

Author -	Pressure node 2 [bar]	Pressure node 3 [bar]
Current study	48.48	48.4
KE and TI	48.1	48
SIMONE	48.25	48.15
K.A. Pambour	48.25	48.15
Osiadacs	48.51	48.5

Pipe flow rates

The computed average pipe flow rates are shown in figure 3.8a. Since for the pipe flow rates no results are provided by (Ke & Ti, 2000) and (Osiadacz, 1987) the computed average pipe flow rates are solely compared with the results of SIMONE and K.A. Pambour. The pipe flow rates of both SIMONE and K.A. Pambour are shown in figure 3.8b.

Characteristic of the computed pipe flow rates are the pipe flow in pipe 1 and 2, both fluctuate with the same pattern as the demand loads. As seen, the pipe flow in pipe 3 remain constant which can be explained by the constant difference between the demand loads and thus the constant in and outlet of pipe 3.



(a) Computed average pipe flow rates

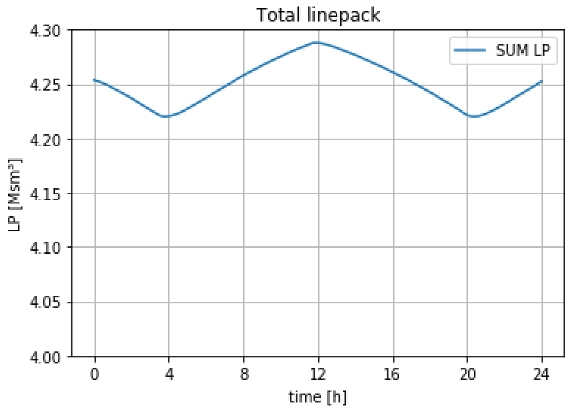
(b) Average pipe flow rates (Pambour et al., 2016)

Figure 3.8: Computed average pipe flow rates

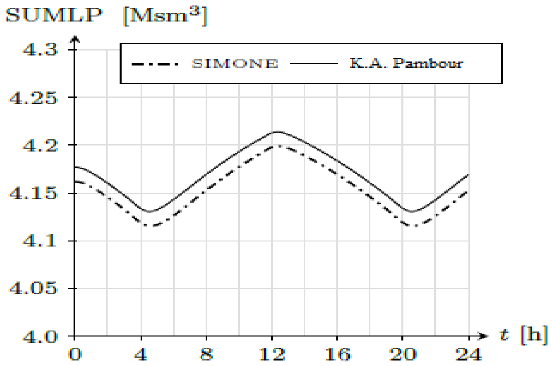
Total linepack

As for the average pipe flow, the total linepack is solely provided by SIMONE and K.A. Pambour and herewith compared. Figure 3.9a shows the computed total linepack for the triangle network. In figure 3.9b the total linepack obtained from literature is shown and table 3.4 show the exact linepack values at the simulation hours 4 and 20 - the hours for which the highest pressure deviation was obtained.

The linepack provides insight in the amount of gas contained within the system and can be viewed as a storage. The maximum deviation (at simulation hour 4 and 20) between the computed total linepack and the total linepack obtained from literature is below 2.5%, table 3.4. Since the linepack is (partially) determined by the average pipe line pressure and the compressibility factor, the deviation is as expected.



(a) Total linepack



(b) Total linepack (Pambour et al., 2016)

Figure 3.9: Total linepack in the triangular gas network

Table 3.4: Triangular network total linepack at simulation hours 4 and 20

Author -	Linepack [Msm^3]
Current study	4.22
SIMONE	4.12
K.A. Pambour	4.14

3.3.2 Diamond network

As a second validation, the diamond network depicted in figure 3.10 is solved. The outcomes of the simulation are compared with the outcomes found within literature (Benner et al., 2018). The reason for solving the diamond network, mentioned by (Benner et al., 2018), was to show the results of a new developed differential algebraic equation (DAE) solver within Python. The within this thesis developed model uses numerical integration to solve the system and thus differs. However, the outcomes can still be compared.

The diamond network consist of seven pipelines and six nodes containing one supply node (node 0) and one demand node (node 5). At the supply node gas is injected into the system with a constant pressure of 80 bar. At the demand node, gas is extracted from the system with a linear demand between 80 and 200 kg/s.

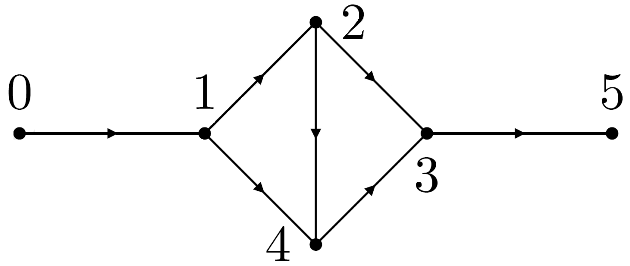


Figure 3.10: Topology of the diamond network (Benner et al., 2018)

Table 3.5: Input parameters transient diamond network

Pipe	Node in - out	Diameter	Length	Roughness
-	-	[m]	[m]	[mm]
1	0 - 1	1.3	9936	0.015
2	1 - 2	1	9392	0.015
3	2 - 3	1.3	7100	0.015
4	2 - 4	1.3	6647	0.015
5	1 - 4	1	4493	0.015
6	4 - 3	1	6287	0.015
6	3 - 5	1	3645	0.015

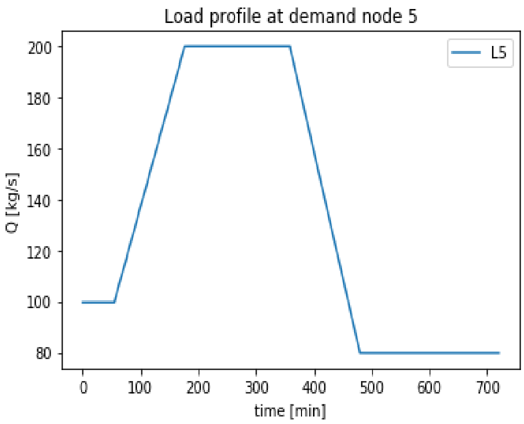
Within literature, no exact simulation time was given. Therefore, the simulation time was read from the graphs as accurate as possible. Also, since no time step was given, a $dt = 180$s as used within the triangular network was used, table 3.6. The same applies for the residual tolerance.

Table 3.6: Simulation parameters for the transient simulation of the diamond gas network

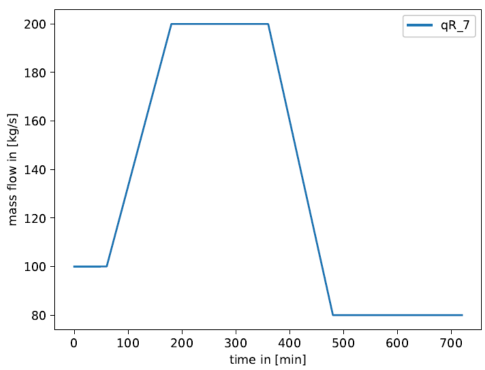
Parameter	Symbol	Value	Unit
Grid segments per pipe	-	1	[-]
Time step	dt	180	[s]
Total simulation time	t_n	12	[h]
Residual tolerance	ϵ	10^{-4}	[-]

Load profiles

The given load profile (boundary condition) of the demand node 5 are found in figure 3.11. In 3.11a the load profile of the model as described in this study is shown and in 3.11b the load profile as found within literature is shown. Since this is an input condition, no deviation is expected here.



(a) Load profile at the demand node 5



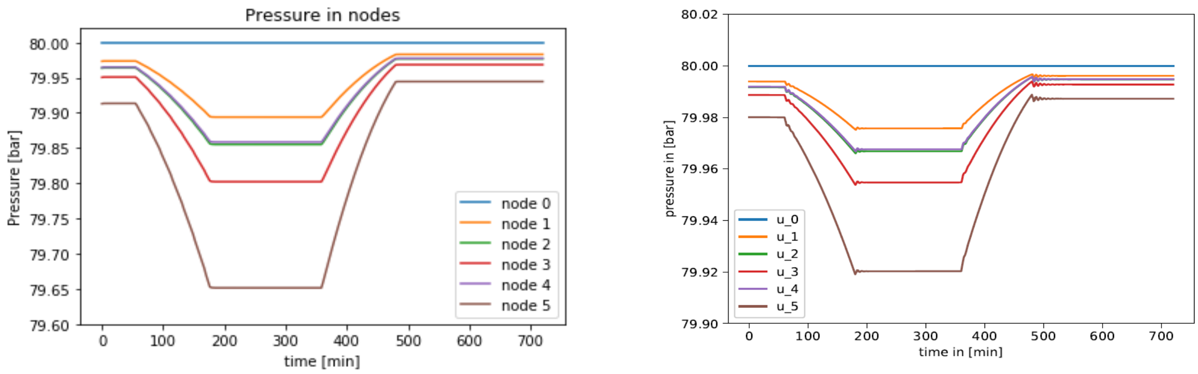
(b) Load profile demand node 5 (Benner et al., 2018)

Figure 3.11: Boundary conditions for the transient simulation of the diamond network

Pressure profiles

Figure 3.12 shows both the computed node pressure profiles and the pressure profiles obtained from literature. Resp. the left graph represent the computed pressure profiles, with node 0 as an input pressure and the right graph shows the values obtained from literature with u_0 as input pressure.

As with the triangle network, the pressure at the demand nodes decrease with an increasing nodal load and increase with a decreasing nodal load. Also, the maximum deviation is less than 1%, concluding reliable outcomes of the model as proposed within this study. When looking sharply to the values in 3.12b, one may notice the sinusoidal course at the start of a change in pressure which is not found in figure 3.12a. This can be explained by the calculation method used. Since this small perturbations in pressure have no impact on the maximum available storage capacity, this difference is neglected.



(a) Boundary (node 0) and the computed pressure profiles

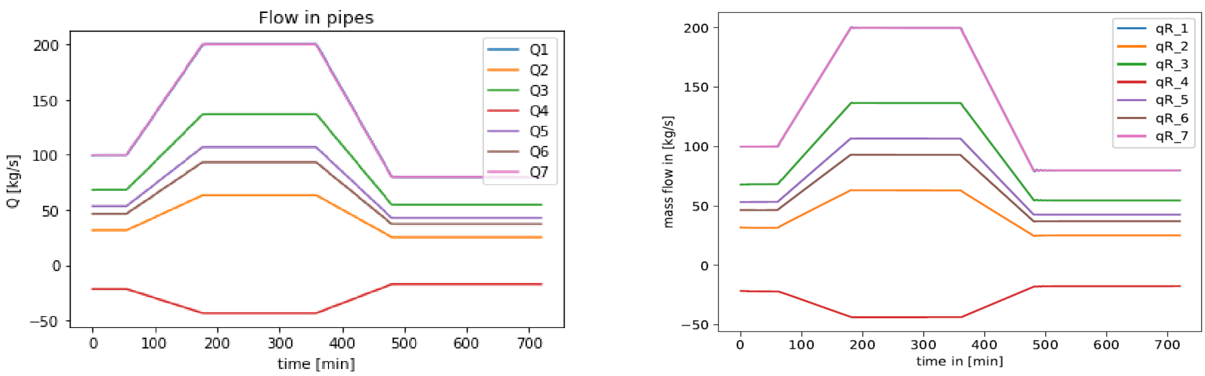
(b) Boundary (U_0) and the pressure profiles at the different nodes (Benner et al., 2018)

Figure 3.12: a) Computed pressure profiles obtained from the model b) Pressure profiles obtained from literature. Note: different scales on the y-axis

Pipe flow rates

Both the computed average pipe flow rates and the average pipe flow rates obtained from literature are shown in figure 3.13.

In figure 3.13a the computed average pipe flow rates are shown. When looking at the graph, a negative flow rate is found (Q4). Physically, a negative pipe flow does not exists and it should be interpreted as a flow in the opposite direction as firstly assumed. As indicated in figure 3.10, the assumed flow direction is from node 2 to 4. However, according to the computed values, in reality the flow direction is from node 4 to 2. Further, comparing the computed pipe flow rates with the pipe flow rates obtained from literature, the exact same values are obtained. Within the study of (Benner et al., 2018) the linepack was not determined.



(a) Computed average pipe flow rates

(b) Average pipe flow rates (Benner et al., 2018)

Figure 3.13: Computed average pipe flow rates for the diamond network

3.3.3 Conclusion

The model as proposed within this study is benchmarked against two different models obtained from literature. Outcomes of the study, obtained for both the models, comply with the solutions obtained from literature. For both the models, the maximum deviation obtained for the pressure is less than 1% and for the triangular model the linepack deviation is less than 2.5%. Given these deviations combined with an 8 bar network, this would give a maximum deviation of ±0.08 bar and is accepted for this study.

4. Casestudy implementation

This chapter elaborates the steps taken for the implementation of a gas distribution network within the model. The implementation of different distribution networks is made generic. Here, the casestudy gas network of Northeast Friesland, The Netherlands is used for explanation. Besides the steps taken to implement a gas network, the different reasons for achieving to certain values are being discussed.

4.1 Simplified casestudy network

In order to define the simplified network, the within Stedin available software Irene Pro is used. Simplification is done according the following predefined steps which where determined in collaboration with Stedin. The steps where determined such that the simulated network replicates the real network as accurate as possible.

- Solely the 8 bar pipelines are considered, the different demands of the lower pressure pipes combined are summed in multiple gas extract points (demand nodes).
- Demand nodes are located at each change in pipe diameter
- Demand nodes are located at a junction of three or more pipes

Looking at the decision to locate a demand node at each pipe diameter change, it should be recalled why this diameter change occurs in the first place. The gas distribution network is engineered in such that gas can be supplied throughout the entire network, within the set boundary conditions. To elaborate, a change in pipe diameter signifies a noticeable difference in gas flow (in- or decrease) as a result of gas being extracted (demand) or injected (city gate station). Therefore, by assuming a demand node at each diameter change, the reality is respected in accordance.

4.1.1 Irene Pro

Irene Pro is a static gas network calculation tool used for e.g., designing networks and the determination of delivery reliability. All the by Stedin employed gas networks are available within Irene Pro. Figure 4.1 shows the casestudy distribution network obtained from Irene Pro. Within this figure, the 8 bar pipelines are depicted bold and the remaining pressure level pipelines and equipment are blurred to give an indication of the remaining pressure level pipes and stations.

The casestudy network is fed by two city gate stations which are indicated as green squares. Also, it can be seen that the network consists of both a loop and a branch which are important to consider within the simplified network.

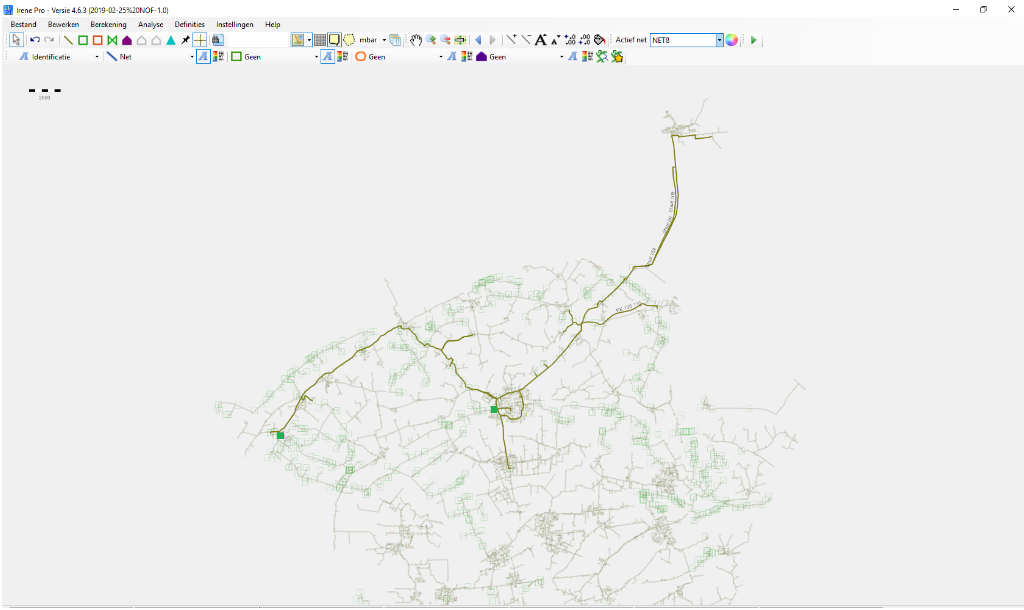


Figure 4.1: Casestudy 8 bar gas distribution network located in Northeast Friesland, The Netherlands

4.1.2 Simplified network

In order to simplify the casestudy network, the previously defined simplification steps are used. Figure 4.2 shows the simplified distribution network.

Within the figure, the demand nodes are indicated with a red dot and both the city gate stations are indicated with a blue dot. Further, the flow direction is indicated in order to mathematically describe the network. The flow direction as indicated within the figure is a presumed direction which may or may not correspond with the real flow direction. The outcomes of the model will indicate the flow direction as a positive of negative value which resp. indicate a flow direction according to the figure and a flow in the opposite direction as given in the figure. The pipe properties can be found in appendix A.1.

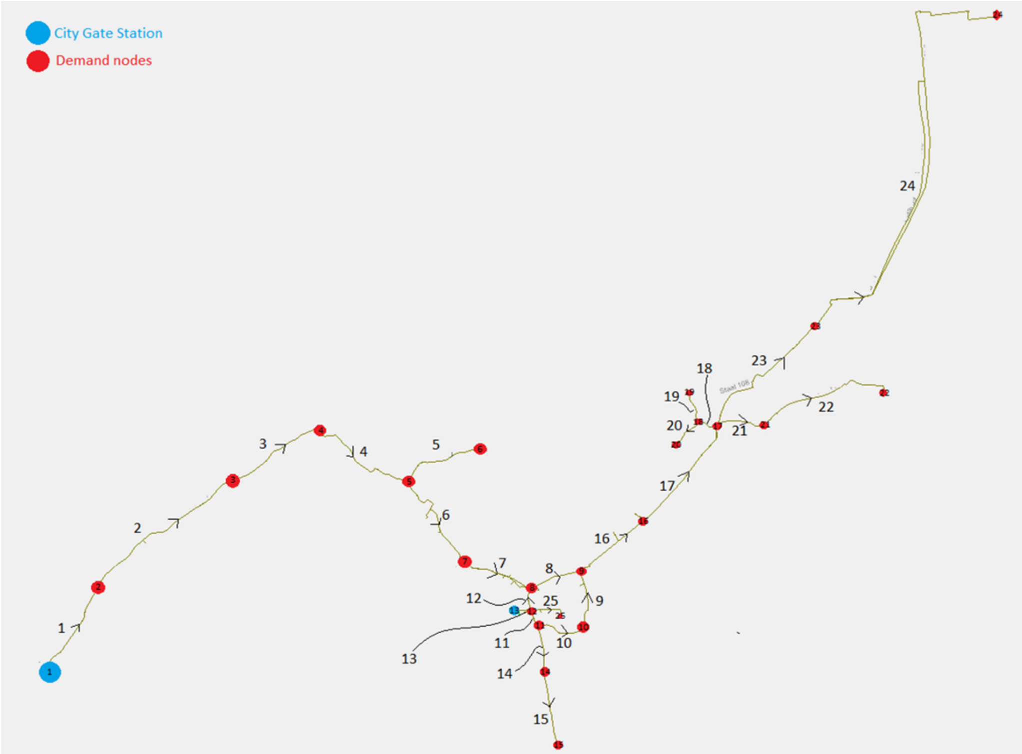


Figure 4.2: Simplified version of the casestudy 8 bar gas distribution network located in Northeast Friesland, The Netherlands

4.2 Demand profile

As mentioned, the demand data of the different district stations are not available within Stedin. Since the hourly injection rate of both the city gate stations is known, these values, combined with the pipe properties available within Irene Pro, are used to define the different demands per node.

Figure 4.3 shows the injection profile of both city gate stations combined from July the 1st to July 7, 2016. When looking at the figure it can be noticed that the gas consumption during weekdays is significantly higher than during the weekend (± hour 20 to 70) - one of the causes for conducting this study.

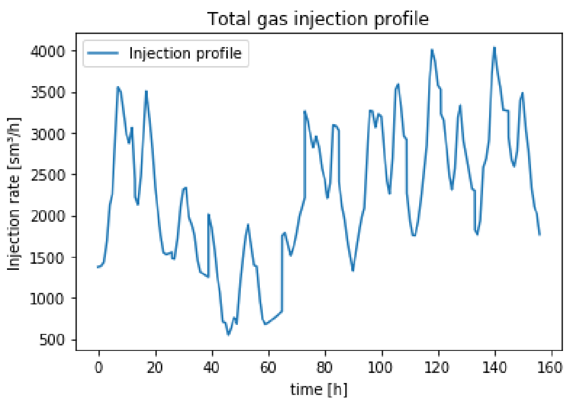


Figure 4.3: Gas injection profile of both the city gate stations combined (01/07/16 to 07/07/16)

4.2.1 Demand per node

In order to define the demand per node it was decided to assign each demand node a percentage of the total injection rate of both city gate stations combined. By doing so, each demand profile at each node will follow the same pattern as the injection rate, though with different values. Reflecting on reality, basically, the big continuous gas consumers (e.g. industry) are lumped together with household consumption and form a new (household) gas consumption profile.

To depict what this method potentially means for the outcomes of the model, an example is given. As we know, pressure drop is related to the amount of gas transported over a certain distance. Therefore, if we have an industrial user located at the furthest point measured from the city gate station, while using 50% of the total gas demand of the network, the pressure drop at this point would in reality be much higher because of the amount of gas to be transported over this distance. However, for the casestudy network, no such situation exists. Given a situation for which this scenario does apply, an extra demand node, using the real demand data, should be applied to the model

In order to define a percentage to a specific demand node, data from Irene Pro is used. The maximum injection rate of both the city gate stations at a specified temperature (the software uses a linear demand profile dependent on the temperature) is determined. Hereafter, the by Irene Pro calculated flow through each pipe is used to determine the gas withdrawal at each node and to calculate the percentage of the total gas injection specified to the node. For a more in depth elaboration of defining the demand percentages per node, see appendix A.1. Figure 4.4 gives an example of the demand profile of node 15 from July the 1st to July 7, 2016. It can be seen that the demand profile is the exact profile as the gas injection profile. Again, a drawback of this method is the exclusion of continuous gas consumers such as hospitals. However, within the casestudy region no continuous gas consumers (fabrics, hospitals etc.) are connected to the grid and thus, for the current case study no impediments caused by continuous gas consumers occur.

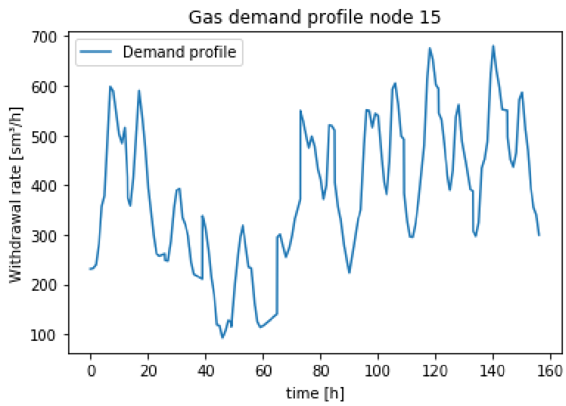


Figure 4.4: Gas demand profile assigned to node 15 (01/07/16 to 07/07/16)

4.3 Green gas supply

Green gas supply nodes are defined in the same manner as demand nodes. The difference between both nodes is the assigned 'demand' value; a green gas node is defined as a negative demand node making it a supply node. Also, the green gas production is a constant process leading to a constant feed in rate. Figure 4.5 gives the total gas demand profile combined with a green gas injection capacity of 1000 m^3/h from 01/07/16 to 07/07/16. During this period, no green gas injection occurred within the network and the depicted 1000 m^3/h green gas injection purely serves illustrative.

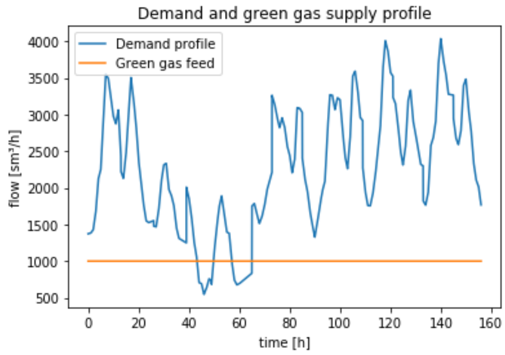


Figure 4.5: Gas demand profile with a continuous green gas injection (01/07/16 to 07/07/16)

4.3.1 Green gas nodes

The location and feed in rate of the different green gas suppliers is defined according available data of the current installed green gas supplier and the open inquiries of potential new green gas suppliers. Figure 4.6 shows the simplified distribution network located in northeast Friesland, including the existing- and potential (open inquiries) green gas suppliers.

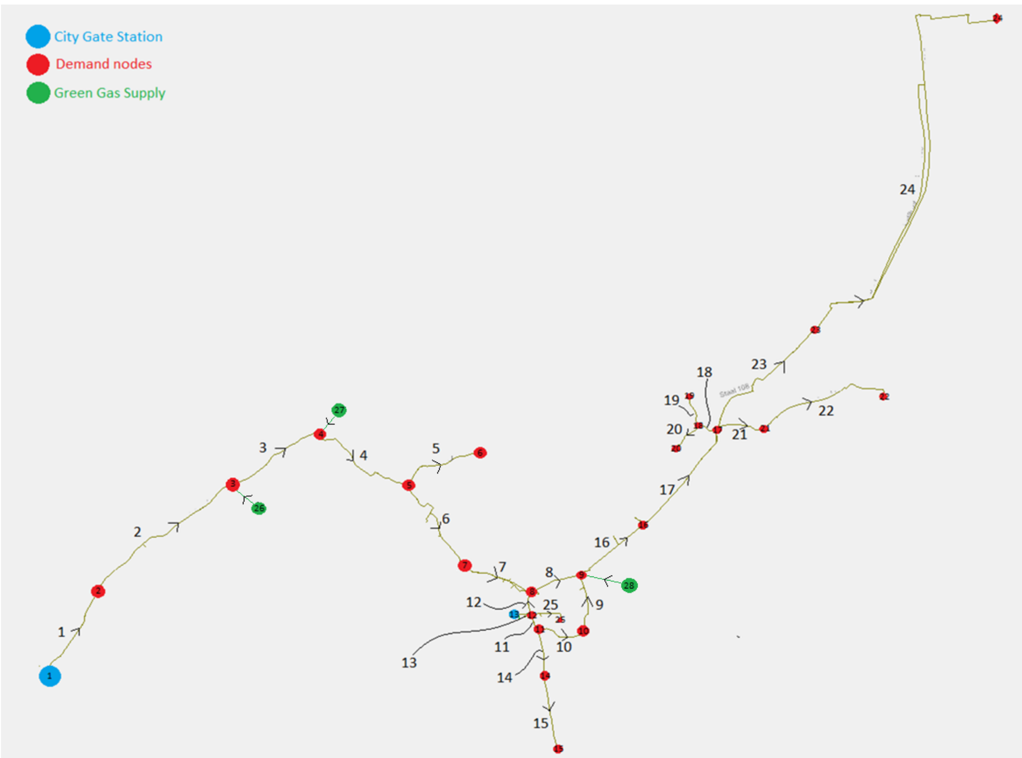


Figure 4.6: Simplified version of the casestudy 8 bar gas distribution network located in Northeast Friesland, The Netherlands including existing and potential green gas suppliers

4.4 Casestudy validation

The results of the casestudy gas network, obtained with the model as proposed within this study, are validated by means of the program Irene Pro. As mentioned, Irene Pro is an analysis tool for designing gas networks, performing network calculations and determining the level of risk or delivery reliability and used by Stedin for managing their own gas networks. With Irene Pro, static calculations are performed.

Within Irene Pro, the demand profile is a linear variable of the outside temperature T, with a lower boundary design temperature of -12°C and an upper boundary temperature of 18°C. For the validation, an outside temperature of 10°C is used. In table 4.1, the validation properties as used within Irene Pro are given.

Table 4.1: Irene Pro validation properties

Parameter	Symbol	Value	Unit
Pressure	p	8	bar
Temperature	T	10	°C
Standard density	ρ_{std}	0.832692	$\frac{kg}{m^3}$
Compressibility	Z	0.9978	-

By using the above parameters, the following results are obtained with Irene Pro, figure 4.7. Within the figure, the obtained values as well as the flow directions are given.

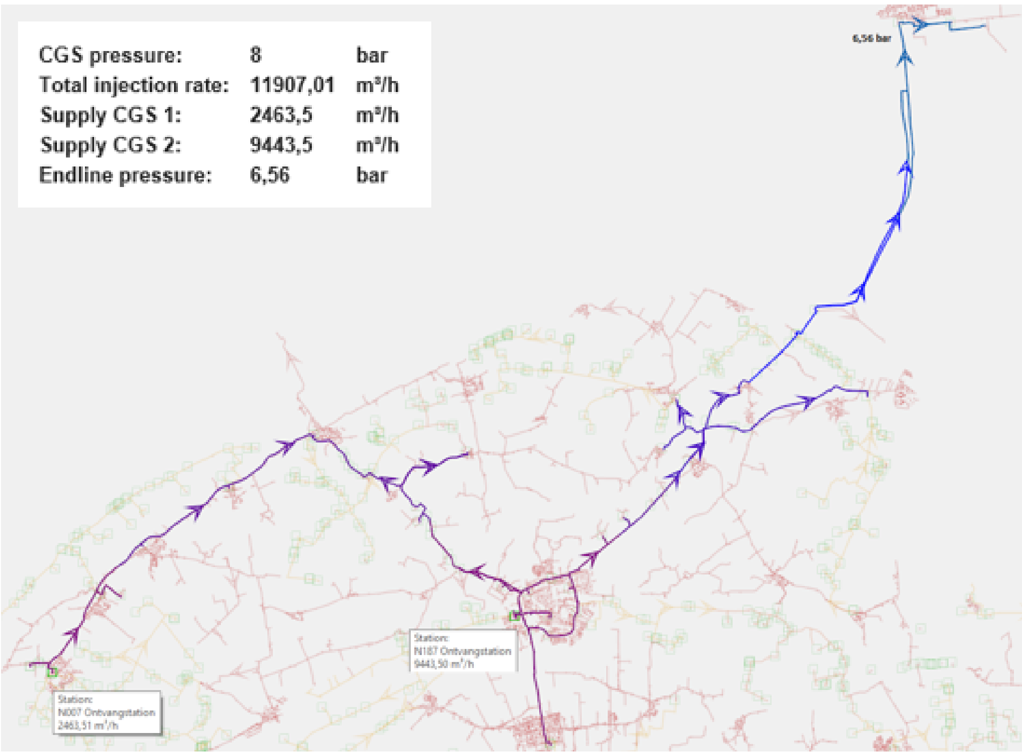


Figure 4.7: Validation results obtained with IrenePro

Since Irene Pro performs a static calculation, for the model proposed within this study, a static demand is given. Further, the inlet pressure of both city gate stations are set to be 8 bar and no green gas is injected into the system. Table 4.2 gives an overview of the properties used within the model.

Table 4.2: Validation properties for the transient gas distribution network simulation modle

Parameter	Symbol	Value	Unit
Gas demand	D	11907.01	$\frac{m^3}{h}$
Pressure	p	8	bar
Standard density	ρ_{std}	0.832692	$\frac{kg}{m^3}$
Compressibility	Z	0.9978	-
Efficiency factor	η_e	0.9	-

Pressure

figure 4.8 shows both the endline pressure obtained with the model as the CGS injection pressure. As can be seen from the figure, the simulation is performed for 12 hours though, since the demand is constant, the simulation time should not have any influence on the obtained values.

The calculated endline pressure obtained with the model is 6.62 bar. Compared with the obtained pressure from Irene Pro, 6.56 bar, the maximum endline pressure deviation is 0.91%. Given the range in which the gas distribution network is operational, 3.5 - 8.5 bar, a maximum deviation of 0.91% is interpreted as precise and certainly acceptable for simulation purposes.

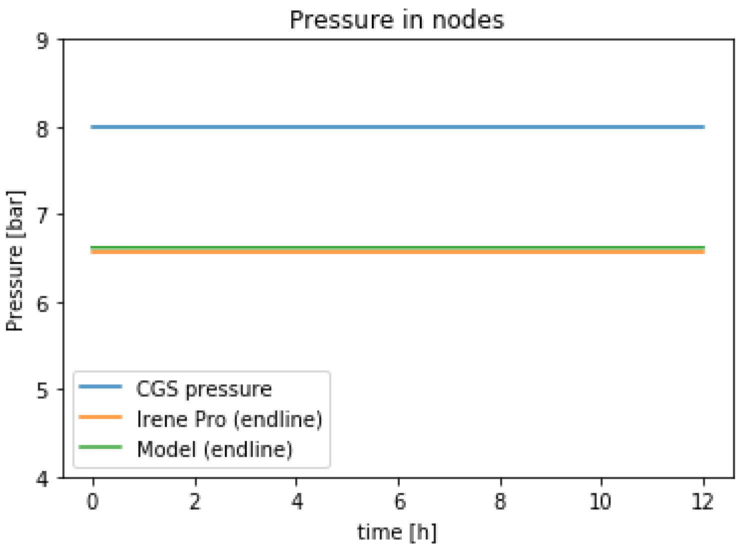


Figure 4.8: Inlet pressure boundary condition of the CGSs and the computed endline pressure of the model and Irene Pro

Pipe flow direction

Here, the computed average pipe flow is validated by means of the flow direction. To clarify, the initial flow directions to describe the mathematics of the proposed model were assumed (4.1.2). As can be seen in figure 4.7, the flow direction obtained by Irene Pro is depicted with arrows. For the model, the flow direction is assigned by a positive or negative value.

The calculated average gas flow is shown in figure 4.9. As seen in the figure, for pipe 4, 6 and 7 a negative flow is obtained which indicates a flow in the opposite direction as the assumed flow direction.

When looking at the assumed flow directions in figure 4.2, the negative flows indeed complies with the flow directions obtained with Irene Pro.

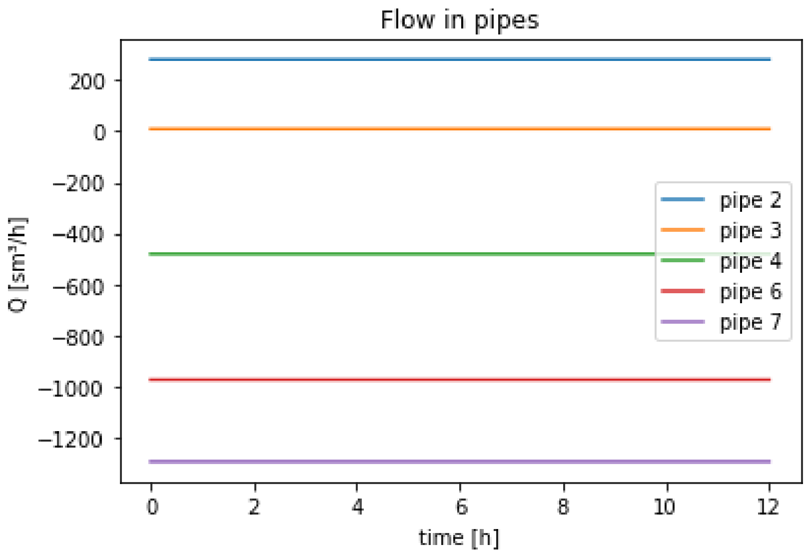


Figure 4.9: Computed average pipe flow rates for which a negative- and positive flow indicate the gas flow direction

Supply per CGS

The casestudy network consist of two city gate stations injecting both a different amount of gas to the system and which combined equal the total gas demand. For both Irene Pro as the model proposed in this study the amount of gas injected by each CGS is obtained.

In figure 4.10 the amount of gas injected by each CGS is given for both Irene Pro as the model. The exact injection rate values of CGS 1 are 2463.5 $\frac{m^3}{h}$ and 2302.5 $\frac{m^3}{h}$ according to resp. Irene Pro and the model. When comparing these values, a maximum deviation of 6.5% is found. The exact injection rates of CGS 2 are resp. 9443.5 $\frac{m^3}{h}$ and 9604.5 $\frac{m^3}{h}$. for Irene Pro and the model. Here, a maximum deviation of 1.7% is found.

The rather high percentage deviation of CGS 1 can be clarified by the simplification process of the casestudy network and the distribution of the demand profiles. Since the focus of the study is not about e.g. optimizing the injection rate of the CGSs but rather on the pressure of the furthest points in the network measured from the city gate stations (minimum pressure boundary condition), a deviation of 6.5% is accepted for this study. To clarify, a deviation of 6.5% in endline pressures will result in incorrect values regarding the green gas injection capacity, and a deviation of the CGS injection rate won't.

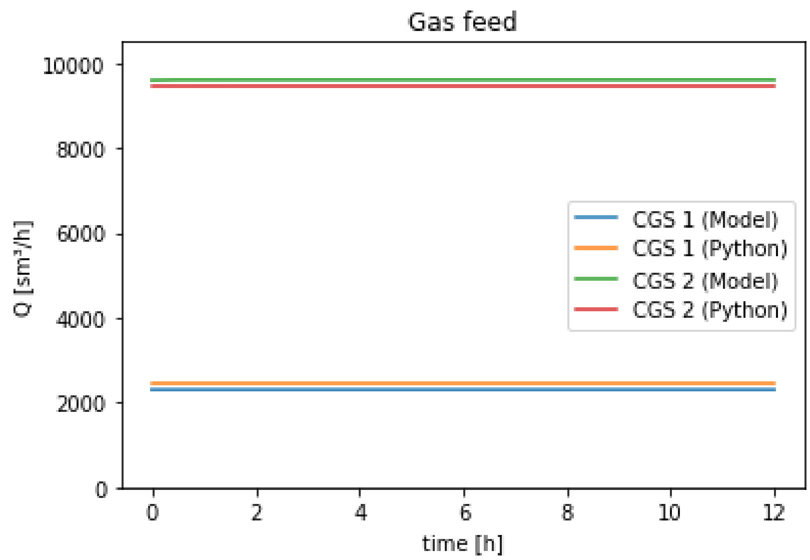


Figure 4.10: Injection rate values of both the city gate stations obtained by the model as proposed within this study and IrenePro

Conclusion

Table 4.3 gives an exact overview of the obtained results with both Irene Pro and the model. For the endline pressure, a maximum deviation of 0.91% is found and for the CGSs 1 and 2 a maximum deviation of resp. 6.5% and 1.7% are found. Given the results, it is concluded that the model as proposed within this study is of sufficient accuracy to perform the analyses as found in chapter 5.

Table 4.3: Validation properties for the transient gas distribution network simulation model

Parameter	Irene Pro	Model	Unit
Endline pressure	6.56	6.62	bar
Supply CGS 1	2463.5	2302.5	$\frac{m^3}{h}$
Supply CGS 2	9443.5	9604.5	$\frac{kg}{m^3}$

5. Simulation results

In this chapter, the developed dynamic gas network simulation model is used to analyse different capacity expanding solutions for the casestudy network in Northeast Friesland, The Netherlands.

First, an elaboration of the simulations - and the desired output data - is given. Second, the network boundaries are described. As third and fourth, the static and dynamic pressure management results are given. Fifth, pressure management simulations combined with a storage are shown and last, a comparison of the different capacity expanding solutions is given.

5.1 Simulation proposals

The model as proposed within this study is developed to give distribution network operators (here, Stedin) a tool to determine the maximum amount of green gas injectable into the gas distribution network by e.g. applying no adjustment to the network, applying static pressure management and/or applying dynamic pressure management. With the outcomes of the model, a substantiated decision can be made whether new green gas suppliers can be allowed for green gas injection and if -or which- capacity expanding solutions are required to provide enough capacity for green gas suppliers. Within this section, the casestudy network is used to elaborate the steps to determine the green gas capacity expansion of the gas distribution network per solution.

5.1.1 Static pressure management

As mentioned in 2.2.1, static pressure management give green gas suppliers the ability to use linepack flexibility achieved by the adjustment of the city gate station(s) inlet pressure(s). However, since the main task of the distribution network operator is to provide gas to all consumers within the network, the network lower pressure boundary condition should always be met and should be carefully taken into account while lowering the CGS inlet pressure and thus within the simulations.

Currently, static pressure management is exploited in some of the working areas of Stedin. If we take the casestudy region Northeast Friesland as an example, the CGSs inlet pressure is adjusted twice a year - in May, the pressure is decreased from 8 to 7 bar and in October, the pressure is increased from 7 to 8 bar. Reason for decreasing the pressure to 7 instead of e.g. 6 or 5 bar is to always fulfill the lower boundary condition and since there is no model available to calculate the potential capacity increment of the pressure adjustment, and because of capacity problems no new green gas suppliers are allowed to the network, there is (currently) no reason to further decrease the CGSs inlet pressures. Regarding the potential capacity increment obtainable with static pressure management - the frequency of which the CGSs are adjusted per year is crucial for the obtained capacity increment, elaborated in the simulation proposal.

Simulation proposal
By simulating static pressure management within the gas distribution network, it is aimed to obtain the capacity increment regarding the injection of green gas while taking into account certain boundary conditions, 5.1. As mentioned before, the frequency at which the CGSs are adjusted per year is crucial for the obtained capacity increment, which can be explained best by an example. As known from the gas flow physics (Chapter 3), the pressure drop within the network is, among others, determined by the gas flow and thus the gas demand - a high demand results in a high pressure drop and vise versa, a low demand results in a small pressure drop. Combining this knowledge with the seasonal variation in gas demand, optimal values can be found regarding the CGSs inlet pressure for different

periods in time - which can further be optimized with the frequency one wants to change the CGSs inlet pressure.

Table 5.1: Simulation parameters and boundary conditions for static pressure management within the gas distribution network

Parameter	Value	Unit
Lower limit pressure	3.5	bar
Upper limit pressure	8.3	bar

With the static pressure management simulations, three results will be obtained, table 5.2. The first goal is to develop a table in which the CGSs inlet pressure will be related to the maximum gas demand within the gas distribution network while maintaining the lower limit pressure boundary condition to ensure gas supply throughout the whole network. Second, with data found from (KNMI, 2016), the on average hottest week - causing the lowest gas consumption - in the year 2016 was determined and simulated with different CGSs inlet pressures and different green gas injection volumes to examine the potential of static pressure management and green gas injection. As third, with the help of the earlier defined CGSs pressure - demand table, the months May, June, July, August and September are simulated to determine the maximum green gas injection capacity while ensuring both the lower- and upper limit pressure within the network. The results of this simulations are used for comparison with the results obtained with the dynamic pressure management solution.

Table 5.2: Goals to obtain with the static pressure management simulations

Nr.	Goal	Simulation period
1	Develop a CGS inlet pressure - gas demand table	-
2	Examine the potential of static pressure management for the casestudy network	On average hottest week of the year, 2016
3	Capacity increment analysis to compare with different solutions	May - October

5.1.2 Dynamic pressure management

As with static pressure management, dynamic pressure management provide green gas suppliers the ability to use the linepack flexibility within the gas distribution network. However, contrary to static pressure management, with dynamic pressure management the adjustment of the city gate stations is automated causing no account to be taken with the frequency of which the CGSs should be adjusted per year.

Simulation proposal
For the dynamic pressure management solution, one simulation is performed, table 5.3. Regarding the simulation period, gas demand data and green gas supply data, the same parameters are used as with the 3th simulation performed with the static pressure management solution. However, as a result of the safety margin for static pressure management (5.2.3), lower CGSs injection pressures are possible for the dynamic simulation resulting in higher green gas injection capacities. The obtained results are analyzed and compared with the results obtained with static pressure management.

Table 5.3: Goals to obtain with the dynamic pressure management simulations

Nr.	Goal	Simulation period
1	Capacity increment analysis to compare with different solutions	May - October

5.1.3 Storage

As mentioned in 2.2.2, distribution network operators (Stedin) are not allowed to manage storage facilities. However, within the model, the possibility for injecting green gas into a storage facility to later inject into the gas distribution network is implemented to identify whether a green gas storage facility on site (at the green gas supplier) would be feasible. Regarding what is - and what is not - feasible, it should be noted that the idea is currently not being exploited by any green gas supplier in contract with Stedin and thus the analysis is purely theoretical to develop an idea of the possibilities of such an on-site storage facility. Therefore, no parameters regarding maximum storage size or pressure under which the gas should be stored are mentioned and should later be determined by the distribution network operator and the green gas supplier.

Simulation proposal
The same simulation period, gas demand data and green gas supply data will be used as with the capacity increment analyses performed for static- and dynamic pressure management. However, within the current simulation, the possibility exist to inject green gas from the storage facility into the gas distribution network causing the storage facility to be filled during periods with low gas demand and emptied during periods with a high gas demand. The obtained results are analyzed to see whether a storage would result in a greater average green gas injection capacity (during the simulation period) and whether the required storage facilities would be feasible to maintain for a green gas supplier.

5.2 Static pressure management

As mentioned, three types of simulations are performed for the static pressure management solution which are elaborated within this section.

5.2.1 Inlet pressure - demand relation

In essence, the difference between static- and dynamic pressure management is the frequency of which the CGS inlet pressure s adjusted. However, where dynamic pressure management responses to measurements within the system by adjusting the CGSs inlet pressures, static pressure management is done manually and thus, knowledge on the amount of gas which can be supported by specific CGS inlet pressures is required.

The simulations, with which the CGS inlet pressure - demand relations are obtained, are performed without green gas injection which means that the network is solely supported by the city gate stations. Inlet pressures between 3.6 and 8.3 bar were simulated with varying constant gas demands which are in- or decreased until the lower limit boundary conditions of 3.5 bar was met within the system. Since a constant gas demand was used to perform the simulations, the outcomes could also be obtained by a steady state gas simulation program (e.g. IrenePro). However, the results of the simulations are required for the two following simulations and thus performed within this study. In table 5.4, the results of the simulations are shown. Because of the simplicity for determining the amount of gas which can be supported by specific CGS inlet pressures, and the possibility to be determined by Irene Pro as well, the steps performed to obtain these results are further not elaborated.

Table 5.4: City gate station inlet pressure - gas demand table

CGS inlet pressure [bar]	Max demand [m^3/h]	Endline pressure [bar]
3.6	2232	3.5
3.7	3178	3.5
3.8	3924	3.5
3.9	4554	3.5
4	5130	3.5
4.5	7498	3.5
5	9468	3.5
5.5	11251	3.5
6	12924	3.5
6.5	14526	3.5
7	16066	3.5
7.5	17589	3.5
8	19076	3.5
8.3	19958	3.5

5.2.2 On average highest temperature week, 2016

First, the week with the on average highest temperature in 2016 was determined with data from (KNMI, 2016). By defining this specific week, it was intended to find the week with the on average lowest gas demand. Also, for the current simulation, Wednesday was assumed to be the first day of the week in order to make optimal usage of the linepack flexibility and the gas demand difference during weekdays and the weekend, as found in figure 1.5.

According to data from (KNMI, 2016), the week with the on average highest temperature in 2016 was from 08/24/16 to 08/30/16 with an average temperature of 19.97 °C. The gas demand data during this period was obtained from Stedin, shown in figure 5.1. Within the graph, the minimum- and maximum gas demand during this period are highlighted. As mentioned before, the maximum green gas injection into the gas distribution network is currently based on the lowest gas demand (Pishbin, 2020), which for this case measures 221 m^3/h. However, by using static pressure management this value can be increased which is simulated below.

Before we start with the simulations, it is important to notice the maximum gas demand during this period which measures 3454 m^3/h. With the results obtained in 5.2.1, found in table 5.4, one find that a minimum CGSs inlet pressure of 3.8 bar should be used in order to support the whole gas distribution network while remaining within the lower limit boundary condition of 3.5 bar.

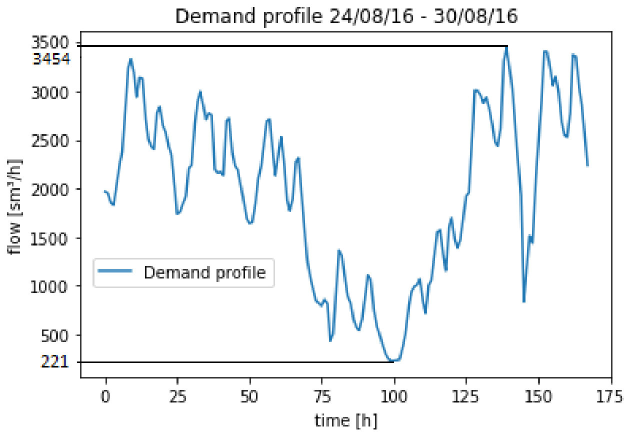


Figure 5.1: Gas demand profile of Northeast Friesland, The Netherlands (08/24/16 to 08/30/16) with the minimum and maximum gas demand highlighted

As found in table 5.4, a minimum CGSs inlet pressure of 3.8 bar is required to support a gas demand of 3453 m^3/h. It should be noted that with the current simulations, it is aimed to inject as much green gas as possible while remaining within the network boundaries. If we look at the real life scenario, a safety factor would be added to the CGSs inlet pressures to ensure a gas supply throughout the network for when the total gas demand unexpectedly increases. The simulations with CGSs inlet pressures 3.8 and 6.5 bar are elaborated extensively wherein in table 5.7 the results of all the simulations are given.

City gate station inlet pressure - 3.8 bar

According the simulations performed with a CGS inlet pressure of 3.8 bar, a maximum green gas injection of 702 m^3/h can be achieved while remaining within the upper limit boundary condition of 8.3 bar. Figure 5.2 depicts the demand profile with a constant green gas injection of 702 m^3/h. As seen within the graph, at times between hour 75 and 105 the green gas supply exceeds the demand which implies that more gas is injected into the system, and thus, the pressure within the system increases. As mentioned before, the simulation period is from Wednesday to Wednesday and it can be noted that in this analysis the supply exceeds the demand during the weekend.

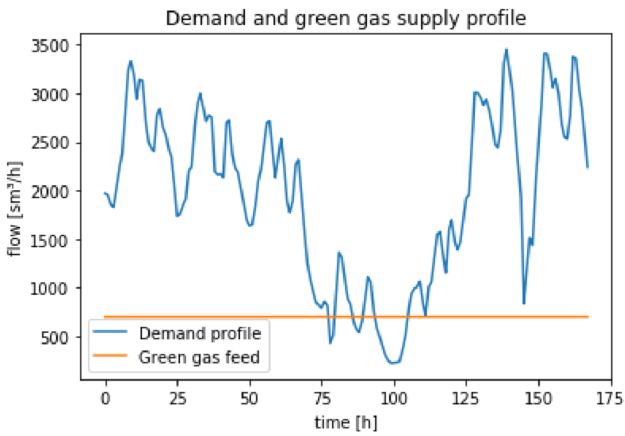


Figure 5.2: Demand and green gas supply profile of Northeast Friesland, The Netherlands

In figure 5.3 the pressure profile of specific points within the gas distribution network is shown with the location of the different nodes found in figure 4.6. Important to note, node 24 is located at the furthest point measured from the city gate stations and the lowest pressure is measured here (lower limit boundary condition). Regarding the other nodes depicted in the figure, these are located near the CGSs and green gas suppliers causing the highest pressure to be measured here (upper limit boundary condition).

Analysing the pressure profile, it can be seen that the pressure within the system from the start of the simulation to hour 75 (Wednesday - Saturday) notes around 3.8 bar (CGS inlet pressure) with, due to friction, an endline pressure of 3.6 bar. From the results found in figure 5.2 - between hours 75 and 105 - at times, the green gas injection exceeds the demand which results in an increased network pressure as seen in the pressure profile graph. The minimum and maximum measured pressure within the system are resp. 3.58 and 8.28 bar both within the system boundaries, table 5.7.

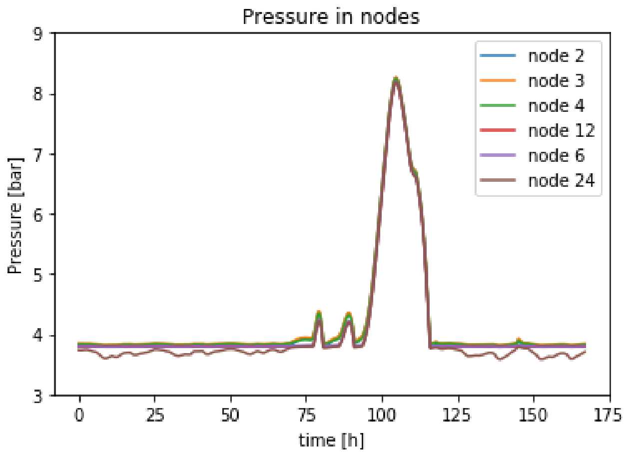


Figure 5.3: Pressure profile of specific points within the gas distribution network in Northeast Friesland, The Netherlands with CGSs inlet pressures of 3.8 bar

Figure 5.4 depicts the gas injection rate of both the city gate stations and the gas injection rates of the green gas suppliers. When looking at the graph, it can be seen that - during hours 75 to 120 - city gate station 1 injects no gas and city gate station 2 only injects gas for small periods of time which is due to the pressure within the gas distribution network. Namely, the CGSs injection pressures are set on 3.8 bar while the pressure within the network is measured higher during this period of time.

If we further look at figure 5.4, we can see that green gas supplier 1, 2 and 3 have a constant feed in rate of resp. 402 m^3/h, 150 m^3/h and 150 m^3/h (depicted as 'G feed'). Reason for green gas supplier 1 to inject noticeably more green gas than supplier 2 and 3 is that supplier 1 is an already existing supplier within the network, where 2 and 3 are not. It was found that the location at which a green gas supplier injects green gas into the network does influence the total injection capacity. However, because of the small differences in injection capacity ($< 1\%$) this will further not be mentioned.

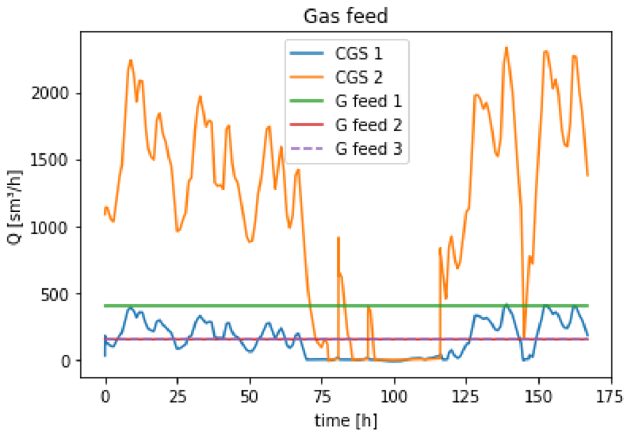


Figure 5.4: Gas injection rate of both the city gate stations and green gas suppliers in Northeast Friesland, The Netherlands

The total linepack of the gas distribution network in Northeast Friesland is depicted in figure 5.5. When looking at the graph, one can see the same pattern as for the pressure profiles in figure 5.3 which is due to the calculation method of the total linepack (mean pipeline pressures). Basically, the available linepack can be seen as a storage where the y-axis depicts the storage capacity. Within the graph, the minimum and maximum linepack are depicted. Here, the minimum linepack is determined with the lower limit pressure boundary condition and the maximum linepack is determined with the upper limit boundary condition. It should be noted that the maximum linepack is not reached within the system (SUM LP) while, according the analysis, no more green gas can be injected into the system. This is explained by the pressure losses which occur within the network. The maximum linepack is determined with an average pressure of 8.3 bar within the whole network whereas for the situation where there is a gas flow within the system, and thus pressure losses occur, the average pressure within the system is less than 8.3 bar.

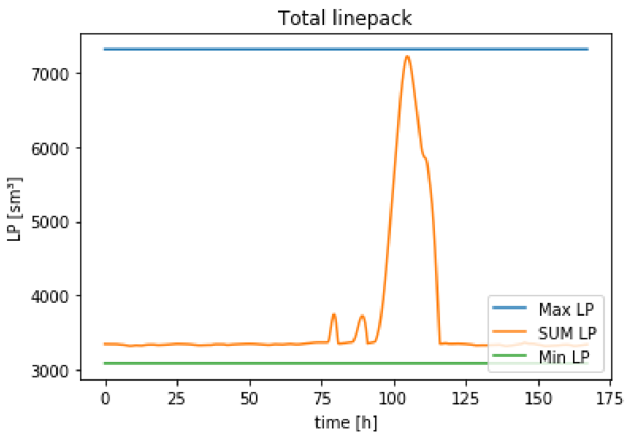


Figure 5.5: Total linepack within the gas distribution network in Northeast Friesland, The Netherlands with CGSs inlet pressures of 3.8 bar

Concluding, with a city gate station inlet pressure of 3.8 bar - during 08/24/16 to 08/30/16 - a maximum green gas injection capacity of 702 m^3/h can be obtained, while without any adjustments to the CGS inlet pressure, a maximum green gas injection capacity of 221 m^3/h is possible, table 5.5 . Here, it should be noted that for the current simulation period the maximum gas demand was 3453 m^3/h and thus a CGS inlet pressure of 3.8 bar was possible whereas when e.g. the next week would have a maximum gas demand of 4500 m^3/h either the CGSs inlet pressure should be increased manually by the operator (to comply with the 4500 m^3/h) or the initial CGSs inlet pressure should be higher. However, since the focus lays on determining the capacity increment potential, this will further not be mentioned.

Table 5.5: Green gas injection capacity increment with a CGS inlet pressure of 3.8 bar

CGS inlet pressure [bar]	Max green gas injection [m^3/h]	Min pressure [bar]	Max pressure	Capacity increment
3.8	702	3.58	8.29	218%

City gate station inlet pressure - 6.5 bar

According the simulations performed with a CGS inlet pressure of 6.5 bar, a maximum green gas injection of 472 m^3/h can be achieved while remaining within the upper limit boundary condition of 8.3 bar. Figure 5.6 depicts the demand profile with a constant green gas injection of 472 m^3/h. As seen within the graph, other than with a green gas injection rate of 702 m^3/h, the green gas supply only exceed the gas demand during one period of time and thus, the pressure within the system will only increase during this period of time.

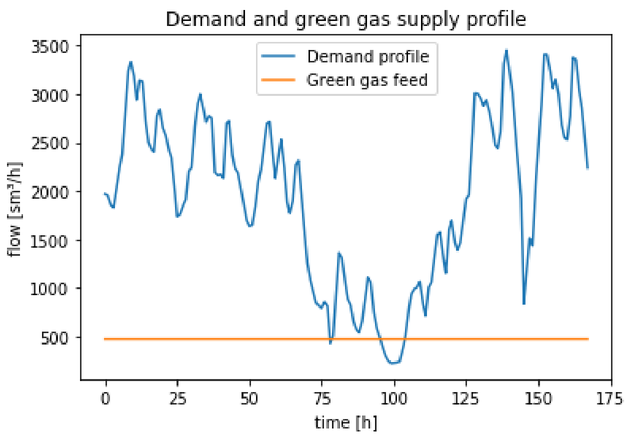


Figure 5.6: Demand and green gas supply profile of Northeast Friesland, The Netherlands

Figure 5.7 shows the pressure profile of specific points within the gas distribution network with the CGSs injecting with 6.5 bar. Regarding the location of the specific nodes, the same counts as with the static pressure management simulation of 3.8 bar. Analysing the pressure profile, it can be seen that the pressure within the system increases during one period of time - where gas supply exceeds the demand. The minimum and maximum measured pressure within the system are resp. 6.37 bar and 8.29 bar, both within the system boundaries, table 5.6.

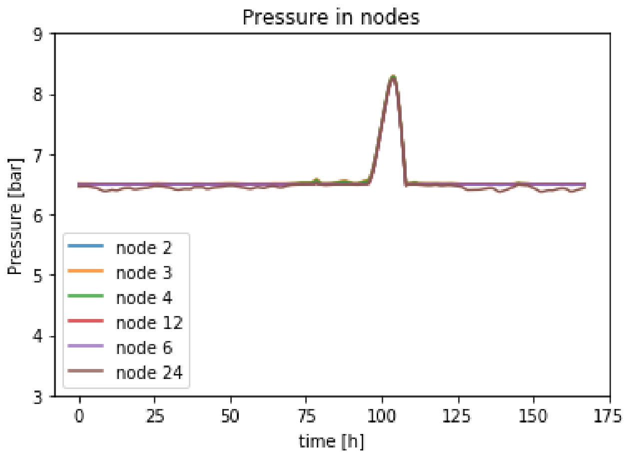


Figure 5.7: Pressure profile of specific points within the gas distribution network in Northeast Friesland, The Netherlands with CGSs inlet pressures of 6.5 bar

Figure 5.8 depicts the gas injection rate of both the city gate stations and the gas injection rates of the green gas suppliers. When looking at the graph, other than with an injection rate of 702 m^3/h, it can be seen that during hours 75 to 120 the city gate station 1 does inject a small amount of gas into the network.

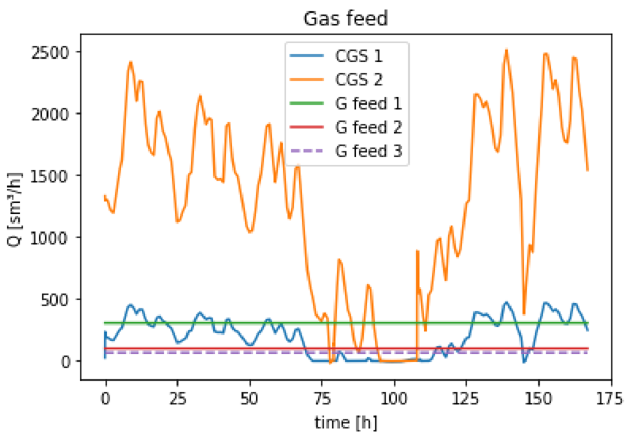


Figure 5.8: Gas injection rate of both the city gate stations and green gas suppliers in Northeast Friesland, The Netherlands

The total linepack of the gas distribution network in Northeast Friesland is depicted in figure 5.9. When we compare the current figure with the linepack figure measured for a CGS inlet pressure of 3.8 bar, it can be noticed that the SUM LP line is shifted from the minimum - to the maximum linepack line which means a higher amount of gas available within the network.

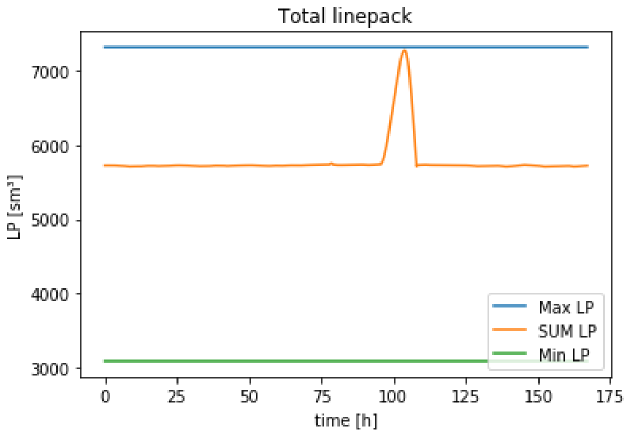


Figure 5.9: Total linepack within the gas distribution network in Northeast Friesland, The Netherlands with CGSs inlet pressures of 6.5 bar

Concluding, with a city gate station inlet pressure of 6.5 bar - during 08/24/16 to 08/30/16 - a maximum green gas injection capacity of 472 m^3/h can be obtained, while without any adjustments to the CGS inlet pressure, a maximum green gas injection capacity of 221 m^3/h is possible, table 5.6.

Table 5.6: Green gas injection capacity increment with a CGS inlet pressure of 6.5 bar

CGS inlet pressure [bar]	Max green gas injection [m^3/h]	Min pressure [bar]	Max pressure [bar]	Capacity increment [-]
6.5	472	6.37	8.29	114%

City gate station inlet pressure table

The results of various static pressure management simulations are shown in table 5.7. Within the table, the first column represents the inlet pressure of the city gate stations, the second column shows the maximum amount of green gas injectable into the system while remaining within the pressure boundary conditions, the third and fourth column shows the minimum and maximum pressure measured within the network, the fifth column gives the capacity increment relative to no inlet pressure adjustments within the network and the last column gives a rough indication of the frequency at which the pressure should be adjusted.

It should be mentioned that, although it is calculated by the simulations, a green gas capacity increment of e.g. 218% is not feasible within real life since this would require a daily - or even higher - frequency of adjustment of the city gate stations inlet pressures. However, the results do give an indication on the potential of dynamic pressure management, as well as an argumentation to determine the frequency of which one decide to adjust the city gate stations inlet pressures.

Table 5.7: Green gas injection capacity increment with varying CGS inlet pressures for Northeast Friesland, The Netherlands

CGS pressure [bar]	Max green gas injection [m^3/h]	Min press [bar]	Max press [bar]	Cap. increment [-]	CGS adjust freq. [-]
3.8	702	3.58	8.29	218%	Hourly
4	688	3.79	8.29	211%	Daily
4.5	649	4.31	8.29	194%	Weekly
5	605	4.83	8.30	174%	Monthly
5.5	557	5.35	8.30	152%	Biannual
6	510	5.86	8.29	131%	Biannual
6.5	472	6.37	8.30	114%	Biannual
7	412	6.88	8.30	86%	Biannual
7.5	355	7.39	8.26	61%	Biannual
8	285	7.9	8.29	29%	Biannual
8.3	221	-	-	0%	-

5.2.3 Capacity increment analysis

In this analysis, the green gas injection capacity is depicted against the maximum injection hours during the period May - October. The simulation period May - October was specified by means of the maximum gas demand measured within a month. In more detail, the maximum measured gas demand in April, 2016 was 13785 m^3/h, the maximum measured gas demand from May to October was 8852 m^3/h and the maximum gas demand in October was 12889 m^3/h. By using table 5.4 one can find the minimum CGSs inlet pressures to support certain gas demands. Combined with the measured maximum monthly gas demands, the static pressure management adjustment is defined and shown in table 5.8. Due to the operational principle of static pressure management, in which an operator is required to statically adjust the CGSs inlet pressures, a safety margin is added to the minimum required inlet pressure. The safety margin was determined in consultation with the distribution network operator (Stedin) and defined at 1.5 bar. Assuming the current adjustment frequency of the CGSs pressures - twice a year - the simulation period May - October was defined. In real life this would mean that on May 1st the CGS inlet pressure is reduced from 8 to 6.5 bar and on September 30, the CGS inlet pressure is increased from 6.5 to 8 bar.

Table 5.8: Maximum measured gas demand in April, May - October and October, 2016 in Northeast Friesland, The Netherlands and the maximum gas demand supportable with the safety CGS injection pressure

Month [-]	Max demand [m^3/h]	Min CGS pressure [bar]	Safety [bar]	CGS pressure [bar]	Supportable demand [m^3/h]
April	13785	6.5	1.5	8	19076
May - October	8852	5	1.5	6.5	14526
October	12889	6	1.5	7.5	17589
Nov - March	19780	8.3	-	8.3	19958

Here, the simulation with gas demand data of May, June, July, August and September, 2016 - with a green gas injection of 750 m^3/h - is elaborated. The writer wants to emphasize that, because of the total simulation time and thus the obtained data, the graphs as shown show rather compressed. However, a good indication on the course of pressure and linepack is obtained and, zoomed in, similar graphs as shown in 5.2.2 are found.

Static pressure management - 750 m^3/h green gas injection

The gas demand and green gas supply from May to October in Northeast Friesland is shown in figure 5.10. As mentioned, the graph does show rather compressed however, looking at the graph, one can notice that at times the green gas supply exceeds the demand and thus injection problems may occur.

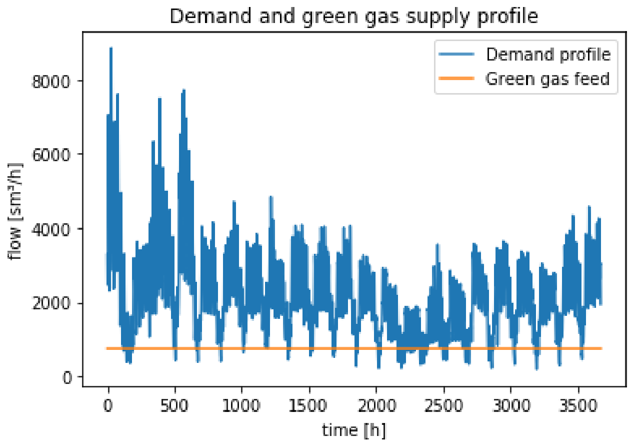


Figure 5.10: Demand and green gas supply profile of Northeast Friesland, The Netherlands from May to October, 2016

Figure 5.11 shows the pressure course during the simulation period of the gas distribution network in Northeast Friesland. The lowest measured pressure within the system is 5.6 bar which occurred in the month May (around hour 100). Looking at the demand and green gas supply profile, it is found that the highest gas demand occurs in May which complies with the lowest measured pressure in May. Another noticeable aspect within the graph are the increases in pressure which occur the most frequent during simulation hours 2000 to 2750 where the gas demand is the lowest. As seen, the pressure within the system never exceeds the upper limit boundary condition of 8.3 bar.

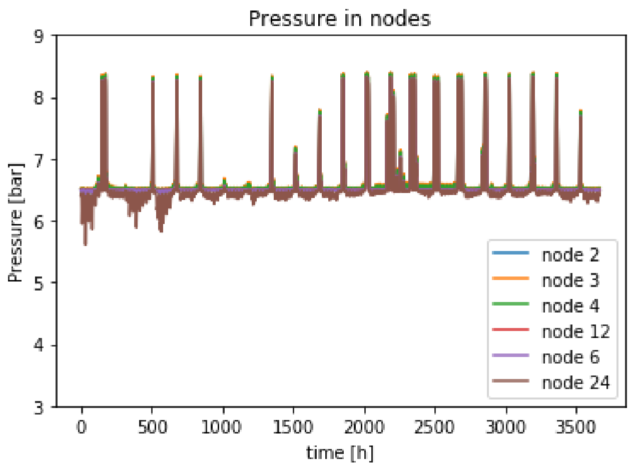


Figure 5.11: Pressure profile of specific points within the gas distribution network in Northeast Friesland, The Netherlands with CGSs inlet pressures of 6.5 bar and 750 m^3/h green gas injection

The linepack within the gas distribution network is shown in figure 5.12. It can be seen that the overall linepack within the system is readily high which is due to the safety margin applied to the

CGSs inlet pressures. Also, as with the increase in pressure, increases in linepack occur. Regarding the model, when either a pressure of 8.3 bar or the maximum linepack is obtained, the green gas injection is reduced to the gas demand in such that a constant in- and outflow occur and the within the network remains constant. If for a period of time only partial green gas injection is possible when either the upper pressure- or linepack boundary limit is hit, the green gas which cannot be injected into the network is fed into a storage as shown in figure 5.13 and the periods of time are accumulated to determine the total hours wherein no injection is possible, later more in detail table 5.9.

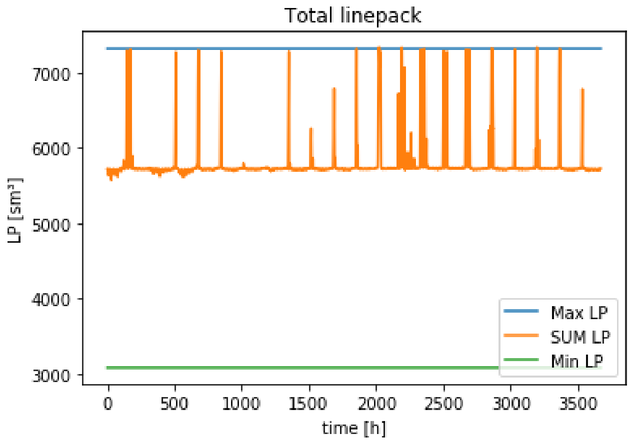


Figure 5.12: Linepack within the gas distribution network in Northeast Friesland, The Netherlands during May, June, July, August and September

Within this analysis green gas injection from storage was not taken into account and therefore, the required storage facility as shown in figure 5.13 is discussed in more detail within section 5.5. However, within this analysis, the total amount of green gas stored is used to distinguish between the hours where no full green gas injection is possible and what this effectively means for the production of the green gas supplier (e.g. the total amount of stored green gas divided by the injection rate defines the missing production hours for the green gas supplier).

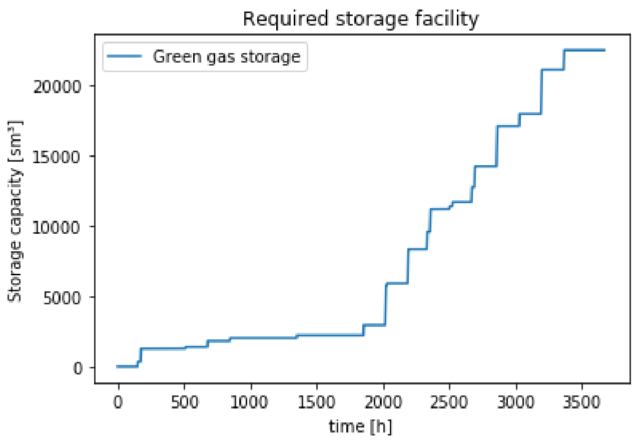


Figure 5.13: Total amount of green gas stored and not injectable into the gas distribution network during May - October

Injectable hours

As discussed in 1.2.1, for a green gas supplier to be eligible for the SDE+ subsidy and to balance its economic exploitation, a green gas supplier is required to inject green gas into the network for a minimum of 8000 hours per year. Using the results obtained from the simulations, the total injectable hours for variable green gas injection capacities are plotted and depicted in figure 5.14.

Table 5.9 gives an overview of the obtained results. To get a better understanding of the meaning of the different outcomes, first, an explanation on how to interpret the different outcomes is given.

- **First column:** Green gas injection capacity. This capacity is the summation of the injection capacities of three separate green gas suppliers.
- **Second column:** Total amount of green gas for which no capacity is available within the gas network summed over the total simulation period.
- **Third column:** The partial hours at which a green gas supplier cannot inject 100% of their green gas into the network. When the pressure within the network reaches the upper limit pressure, (gas demand < supply), the green gas injection equals the total demand while the rest of the produced green gas is injected into the storage facility. By using figure 5.12, the total linepack, the frequency at which partial injection occurs can be extracted. Partial injection occurs when the total linepack reaches the upper limit boundary condition.
- **Fourth column:** Effective hours wherein no injection is possible. Knowing the hours at which only partial injection is possible does not provide us with any information on the missing production hours. Therefore, using equation (5.1), the effective hours hours wherein no injection is possible are determined.

$$eff.\,hours\,no\,injection = \frac{storage\,volume}{Green\,gas\,injection} \tag{5.1}$$

- **Fifth column:** Hours of full injection. Here, the partial hours at which green gas suppliers cannot inject 100% of their green gas into the network is subtracted from the total simulation period. Note, the performed simulations measure 3671 instead of 8760 hours (full year). However, given that green gas injection problems occur during periods of low gas demand (simulation period) no injection problems are expected during the rest of the year and thus, the shown results could be extrapolated to a full year, 8760 hours.

Table 5.9: Variable green gas capacities with their injectable hours during May - October, 2016 in Northeast Friesland, The Netherlands

Green gas inj. [m^3/h]	Req. storage volume [sm^3]	Partial hrs no inj. [h]	eff. hrs no inj. [h]	Total inj. hrs [h]
400	0	0	0	3671
450	0	0	0	3671
500	947	8,15	1,89	3663
550	2761	14,06	5,02	3657
600	5018	24,05	8,36	3647
650	9042	39,06	13,91	3632
700	14675	56,20	20,96	3615
750	22518	82,95	30,02	3588
800	33082	110,05	41,35	3561
850	45926	140,40	54,07	3531
900	61074	171,40	67,86	3500
950	79193	210,15	83,36	3461
1000	99777	257,50	99,78	3414
1050	122264	305,85	116,44	3365
1100	146963	356,45	133,60	3315
1150	173182	394,40	150,59	3277
1200	203620	447,75	169,68	3223
1250	237446	517	189,96	3154
1300	274996	582,90	211,54	3088
1350	315812	643,20	233,93	3028
1400	360249	705,10	257,32	2966
1450	408789	771,3	281,92	2900
1500	460941	839,90	307,29	2831
1550	516600	911,35	333,29	2760
1600	573018	963,70	358,14	2707

The total injectable hours for variable green gas capacities are depicted within figure 5.14. Looking at the graph, one could say that the injectable hours show an exponential decay as the green gas injection capacity increase - with an green gas injection capacity of 450 m^3/h the full 3671 hours are injectable where with an injection capacity of 1600 m^3/h solely 2707 of the total 3671 hours are fully injectable. The graph as shown will later be used for comparison with the dynamic pressure management solution, section 5.4

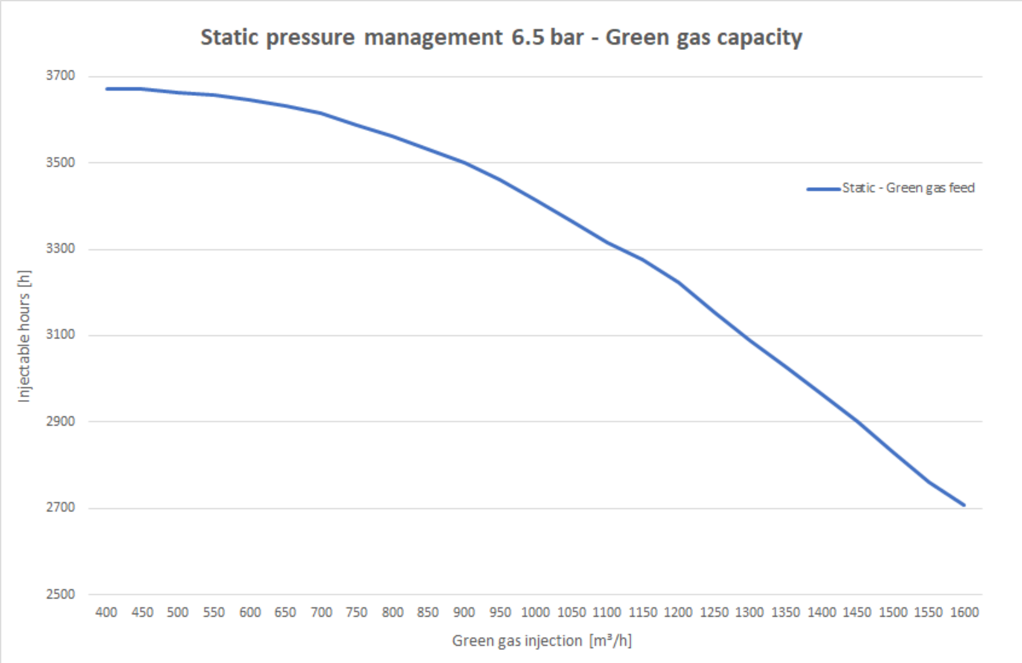


Figure 5.14: Static pressure management green gas injection capacity plotted against the injectable hours during the simulation period from May to October

5.3 Dynamic pressure management

As mentioned, only one simulation is performed for the dynamic pressure management solution which is elaborated within this section and later compared with the solutions obtained with the static pressure management analysis. The writer wants to emphasize that, for dynamic pressure management, currently no clear system control protocol is known by Stedin (DSO) since the solution as modelled is not applied within one of their systems (yet). Therefore, a few assumptions regarding the minimum pressure, and in- and decrease of the inlet pressure are made and given in table 5.10. It was assumed that, as a safety margin, the minimum CGSs inlet pressures are 4 instead of 3.5 bar. Also, pressure in- and decrease are performed with 0.2 bar per step.

Table 5.10: Modelling assumptions used for the modelling of dynamic pressure management

Assumption	Value
Lower limit city gate station inlet pressure	4 bar
Pressure increase per timestep	0.2 bar
Pressure decrease per timestep	0.2 bar

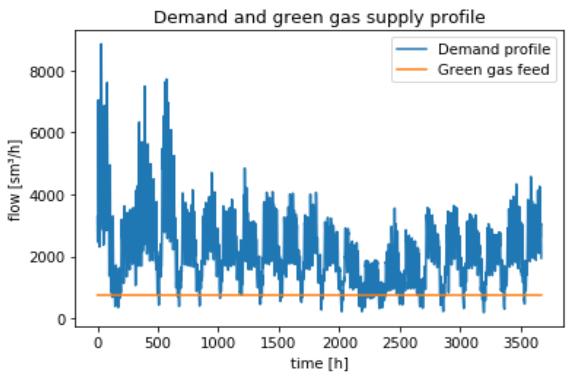
5.3.1 Capacity increment analysis

In this analysis, as with the capacity increment analysis performed for static pressure management, the green gas injection capacity is depicted against the maximum injection hours during the period May - October. Although for dynamic pressure management the city gate station inlet pressures are adjusted continuously, and thus has no necessity for a specific simulation period, the same period as for the static pressure management adjustment is simulated in order to compare both solutions.

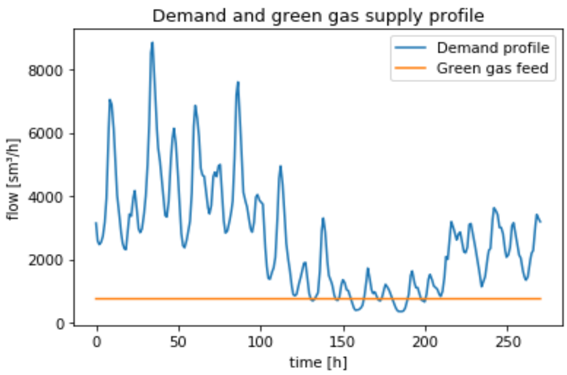
The simulation with gas demand data of May, June, July, August and September, 2016 - with a green gas injection of 750 m^3/h - is elaborated. Since the total simulation time, as with the static pressure management Again, as a result of the simulation time, the graphs show rather compressed and thus both the total simulation period - as the first 250 simulation hours are shown.

Dynamic pressure management - 750 m^3/h green gas injection

The gas demand and green gas supply from May to October in Northeast Friesland, the Netherlands is shown in figure 5.15a. Since the demand or supply is not influenced by the pressure management method - static or dynamic - the same profile is found in figure 5.10. Within the right graph, figure 5.15b, the demand and green gas supply of the first 250 hours of the simulation are shown. As can be seen, during the first 250 hours of the simulation, both periods occur where the demand exceeds the green gas supply as where the supply exceeds the demand.



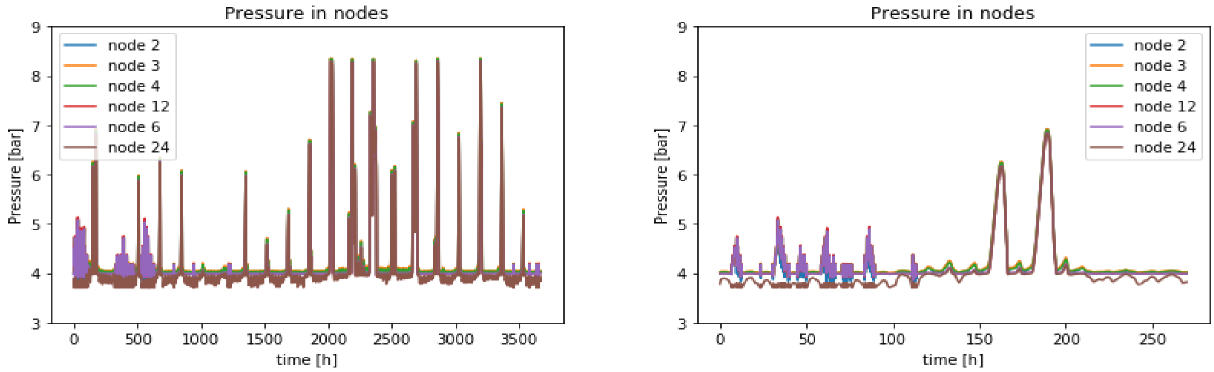
(a) Demand and green gas supply profile from May to October, 2016



(b) 250 hours within the simulation period

Figure 5.15: Demand and green gas supply profile of Northeast Friesland, The Netherlands from May to October, 2016

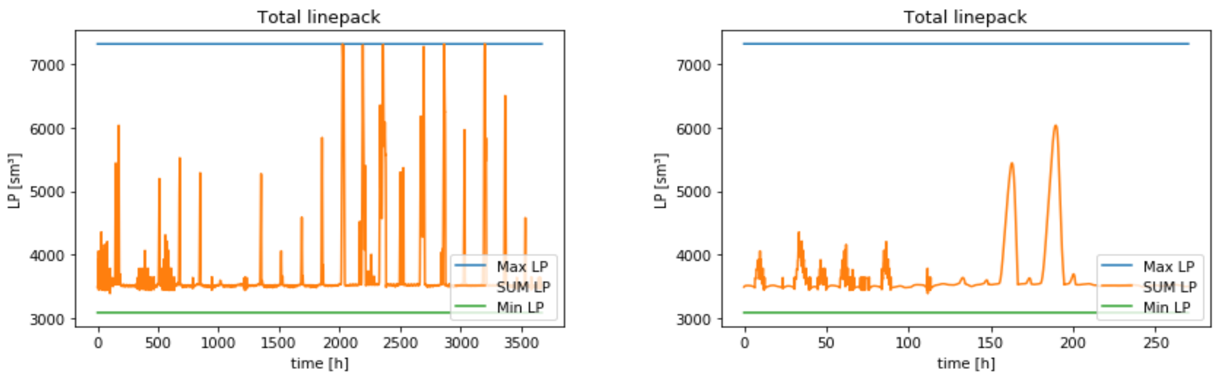
Figure 5.16a shows the pressure course during the simulation period of the gas distribution network in Northeast Friesland. When we focus on the first 250 hours of the pressure course, figure 5.16b, it can be seen that during the first 100 hours the pressure increases while, figure 5.15b, the demand exceeds the supply. During these in- and decreases in pressure, the dynamic pressure management is operational and reacts on the in- and decrease of the gas demand. Also, for the first 100 hours, it can be seen that the pressure drop in node 24 (endline pressure) is readily high which is justified by the associated gas demand. During the first 250 hours, the pressure remains within the boundary conditions and all the green gas can be injected into the network.



(a) May to October, 2016 (b) 250 hours within the simulation period

Figure 5.16: Pressure profile of specific points within the gas distribution network in Northeast Friesland, The Netherlands with dynamic pressure management and 750 m^3/h green gas injection

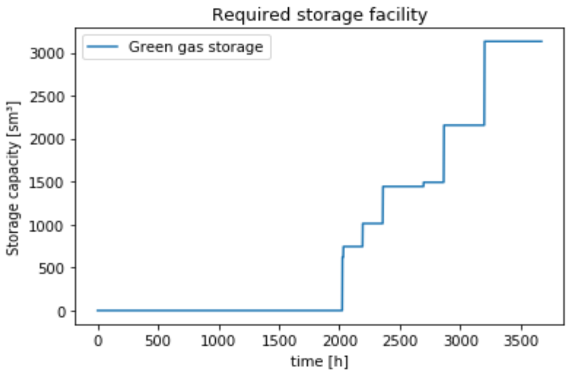
The linepack within the gas distribution network is shown in figure 5.17. As earlier mentioned, when either a pressure of 8.3 bar - or the maximum linepack - is obtained, the green gas injection is reduced to the gas demand in such that a constant in- and outflow occur and the pressure within the network remains constant. Looking at the linepack shown in figure 5.17a, one notices 6 periods in time where the linepack within the network equals the upper limit boundary condition. During these periods, no- or no full green gas injection is possible and part of the green gas is injected into the storage facility, figure 5.18.



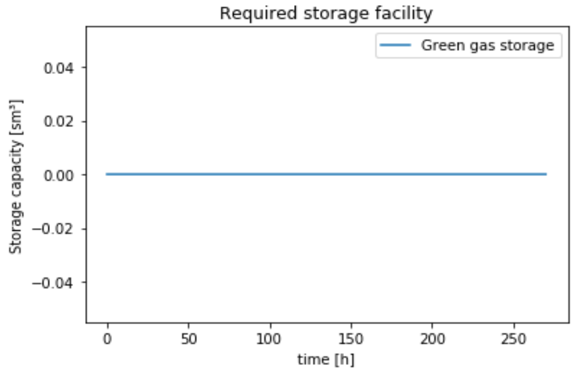
(a) May to October, 2016 (b) 250 hours within the simulation period

Figure 5.17: Linepack within the gas distribution network in Northeast Friesland, The Netherlands with dynamic pressure management and 750 m^3/h green gas injection

Again, as within the static pressure management analysis, the green gas injection from storage was not taken into account and used to distinguish between the hours where no full green gas injection is possible and what this effectively means for the production of the green gas supplier. As can be seen in figure 5.18b, within the first 250 hours of the simulation period, all the green gas is injected into the distribution network which is according the obtained pressure and linepack results of the first 250 simulation hours. Also, looking at figure 5.18a, it can be noted that their are 6 periods in time where the storage is filled, which complies with the earlier mentioned 6 periods in time where the linepack within the network equals the upper limit boundary condition.



(a) May to October, 2016



(b) First 250 hours of the simulation period (no storage required during this period and thus = 0)

Figure 5.18: Total amount of green gas stored and not injectable into the gas distribution network

Table 5.11 gives an overview of the obtained results with dynamic pressure management.

Table 5.11: Variable green gas capacities with their injectable hours during May - October, 2016 in Northeast Friesland, The Netherlands with dynamic pressure management

Green gas inj. [m^3/h]	Req. storage volume [sm^3]	Partial hrs no inj. [h]	eff. hrs no inj. [h]	Total inj. hrs [h]
400	0	0	0	3671
450	0	0	0	3671
500	0	0	0	3671
550	0	0	0	3671
600	0	0	0	3671
650	0	0	0	3671
700	588	4,55	0,80	3666
750	3131	17,50	4,20	3654
800	9327	36,50	11,70	3635
850	16734	58,65	19,70	3612
900	27957	91,40	31,10	3580
950	43706	126,90	46	3544
1000	61881	170,05	62	3501
1050	81994	216,5	78	3455
1100	104363	264,10	95	3407
1150	128327	304,10	112	3367
1200	154566	347,15	129	3324
1250	184918	408,25	148	3263
1300	220932	464,60	170	3206
1350	261563	517,25	194	3154
1400	305640	576,60	218	3094
1450	351641	632,30	243	3039
1500	401577	702,35	268	2969
1550	453248	772,60	292	2898
1600	507463	835,10	317	2836

The total injectable hours for variable green gas capacities are depicted within figure 5.19. The injectable hours show an exponential decay with the ability to inject up to 650 m^3/h green gas for 100% of the time where for 1600 m^3/h green gas injection 2836 of the in total 3671 hours are fully injectable. The graph as shown is later used for comparison with the static pressure management solution, section 5.4

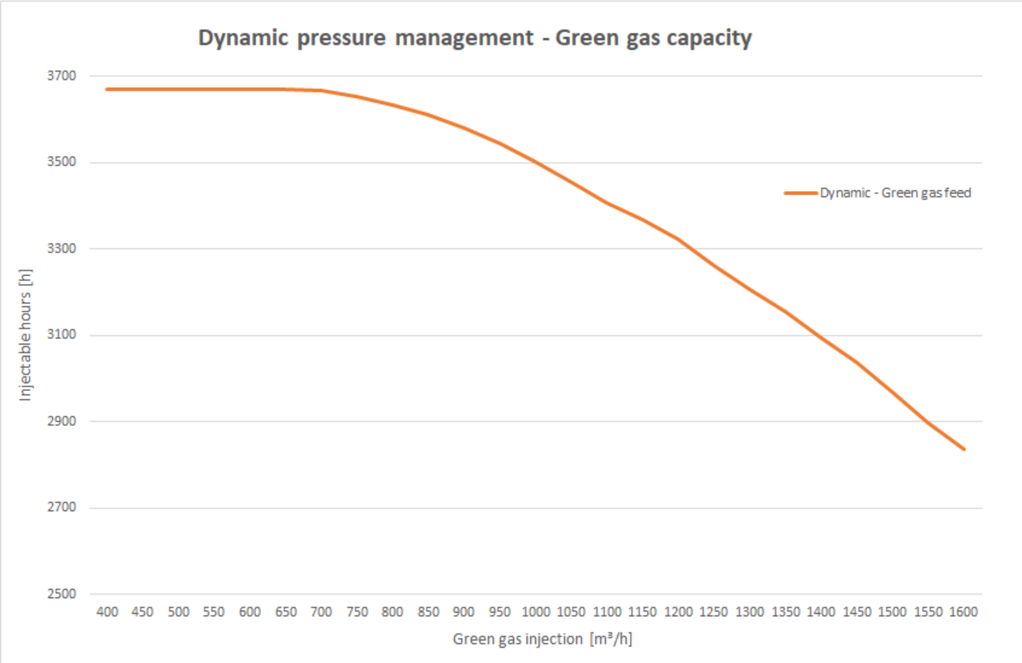


Figure 5.19: Dynamic pressure management green gas injection capacity plotted against the injectable hours during the simulation period May to October

5.4 Pressure management comparison

Within this section, the results of both the static- and dynamic pressure management solutions are compared. The comparison focuses on capacity- and capacity increment.

5.4.1 Capacity comparison

The capacity increment of both the static- and dynamic pressure management solution are plotted and shown in figure 5.20. At first glance, it is noted that the dynamic pressure management solution results in a greater capacity increment compared to static pressure management, which is the result of a lower CGSs inlet pressure. Also, for dynamic pressure management, a higher capacity can be injected into the gas distribution network while maintaining the ability to inject the full 3671 hours, table 5.12.

Table 5.12: Maximum green gas injection capacity which is continuously injectable into the gas distribution network Northeast Friesland, The Netherlands

Continuous green gas injection upper limit	
Static pressure management	450 m^3/h
Dynamic pressure management	650 m^3/h

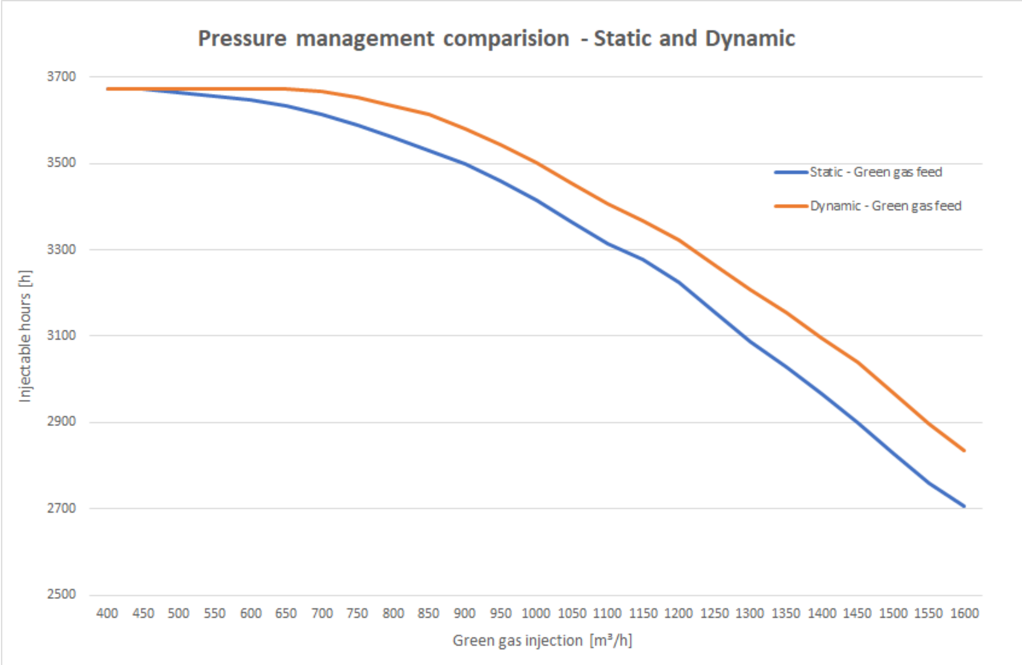


Figure 5.20: Green gas injection capacity of both static- and dynamic pressure management plotted against the injectable hours

Where in figure 5.20 the green gas injection capacity of both the static- and dynamic pressure management are depicted against the injectable hours, figure 5.21 depicts the green gas injection capacity of both pressure management solutions against the green gas capacity which cannot be injected into the gas distribution network during the simulation period.

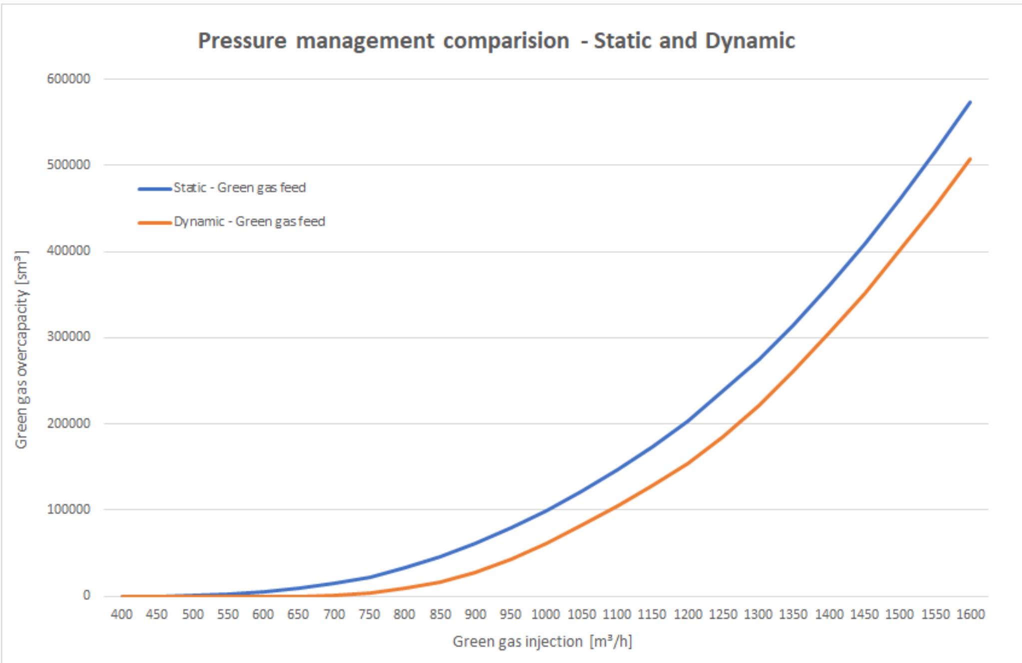
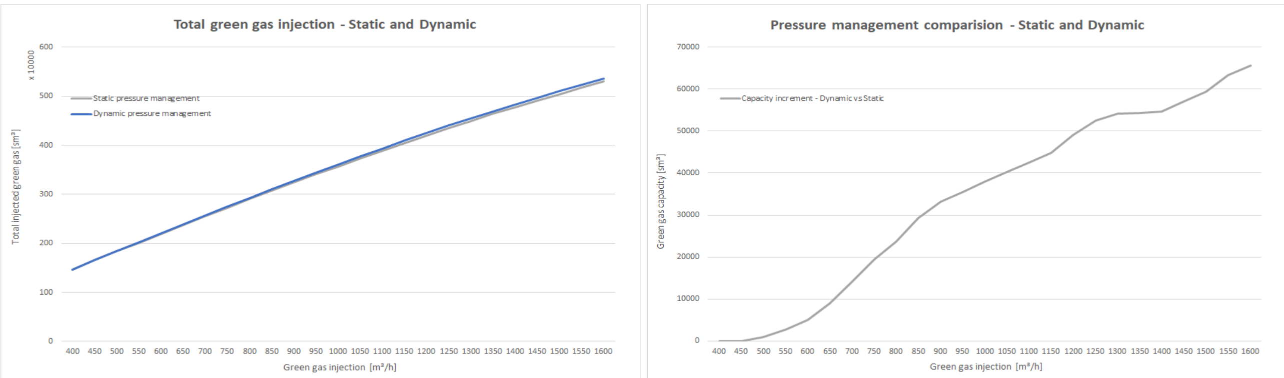


Figure 5.21: Green gas injection capacity of both static- and dynamic pressure management plotted against the volume green gas which is not injectable into the gas distribution network

In figure 5.22 the total amount of green gas injected during the simulation period- and the difference in injection capacity between static- and dynamic pressure management are shown. Within figure 5.22a, it can be seen that with an injection capacity of 1600 m^3/h a total of $5.30 \cdot 10^6$ and $5.36 \cdot 10^6$ green gas is injected with resp. static- and dynamic pressure management during the total simulation period.

Within figure 5.22b, the difference in injection capacity between both solutions is obtained by extracting the total green gas injection volumes in figure 5.22a. Looking at figure 5.22b, one notices that the increase in capacity is rather bumpy - instead of a straight line - which is due to a combination of reasons. First, since the values within figure 5.22b are obtained by extracting the total green gas injection volumes, one could say that the graph is 'zoomed in' and magnifies accuracy deviations - to elaborate, the capacity increment ($6.6 \cdot 10^4$ sm^3 with 1600 m^3/h green gas injection) obtained with dynamic pressure management accounts for 1.22% of the total injected green gas volume ($5.36 \cdot 10^6$ sm^3). However, this does not mean that the deviation is not here though it is mentioned for the reader to make notice.

The bumpy - instead of straight - line is declared by the time step and the maximum pressure boundary condition within the model, which is clarified by an example. If, for example, the network has reached a pressure of 8.28 bar and, lets say, there is room for 40 sm^3 green gas injection before the network reaches the upper limit pressure boundary condition of 8.3 bar, we could inject 40 sm^3 to fill the network. However, if per time step 60 sm^3 green gas is injected, the upper limit pressure boundary would be exceeded and thus for this time step the model assumes a green gas injection which is equal to the demand to not further increase the pressure - leaving the potential 40 sm^3 unfilled.



(a) Total green gas injection

(b) Capacity increment

Figure 5.22: Total green gas injection - and capacity difference - of both static- and dynamic pressure management for different injection capacities for the casestudy network in Northeast Friesland, The Netherlands

5.4.2 Conclusion

Following the outcomes of both analyses, with dynamic pressure pressure management, more green gas injection capacity is obtained within the gas distribution network as with static pressure management. Where with a static pressure management adjustment to 6.5 bar a maximum continuous green gas injection of 450 m^3/h can be obtained, with dynamic pressure management a maximum continuous injection of 650 m^3/h can be reached.

5.5 Storage

Within this section, simulations wherein static- or dynamic pressure management is combined with a storage facility are elaborated. Simulations wherein solely a storage facility, without any pressure management strategy, is being used are not performed. Reason for not doing this analyses is that currently already static pressure management is applied to the casestudy network and thus, for this casestudy, it would not be likely not to apply static pressure management and instead only use a storage facility. However, the model is capable of performing such analyses wherein solely a storage facility is used.

As mentioned, the storage facility as used within the simulations is not exploited within the current gas distribution network and therefore, assumptions regarding the filling and emptying of the storage facility are done, table 5.13. Regarding filling the storage, when either the upper limit pressure- or upper limit linepack boundary condition within the network is reached, part- or all of the green gas is injected into the gas storage facility. For withdrawing gas from the storage, to inject into the gas distribution network, the assumption was made that one - or both - CGSs are injecting. Physically this means that the pressure within the network, near one or both CGSs, is less than the CGS injection pressure and thus the network has capacity for extra green gas injection. The amount of gas injected in - or withdrawn from - the storage was determined in such a manner that percentage wise each green gas supplier injects the same in - and withdraws the same from - the storage facility. At last, an injection capacity from the storage facility into the network of 300 m^3/h was assumed. Note, this assumed 300 m^3/h is a variable dependent on e.g. the compressor used at the green gas supplier, and will become more apparent if used in real life.

Table 5.13: Modelling assumptions used for the modelling of static- and dynamic pressure management combined with a gas storage facility

Condition	Action
Upper pressure or linepack boundary reached	Injecting gas into the storage facility
One or both CGSs injecting and 300 m^3 gas within storage	Injecting gas from storage to network

5.5.1 Capacity increment analysis - Static with storage

Within this analysis, as in the capacity increment analyses performed for the static- and dynamic pressure management, the green gas injection capacity is depicted against the maximum injection hours during the period May - October. However, where in the previous simulations the storage was simulated as storage only, within this analysis the green gas stored can be injected into the gas distribution network.

The focus of the analysis is on the required volume of the storage tank. The simulation is performed with 1600 m^3/h green gas injection which resulted for static pressure management in a required storage volume of $5.7 \cdot 10^5$ sm^3 and for dynamic pressure management in a required storage volume of $5.1 \cdot 10^5$ sm^3, table 5.14. The outcomes of the current simulation will be compared and analyzed. Again, as a result of the simulation time, the graphs show rather compressed and both the total - as a part of the simulation time - are shown.

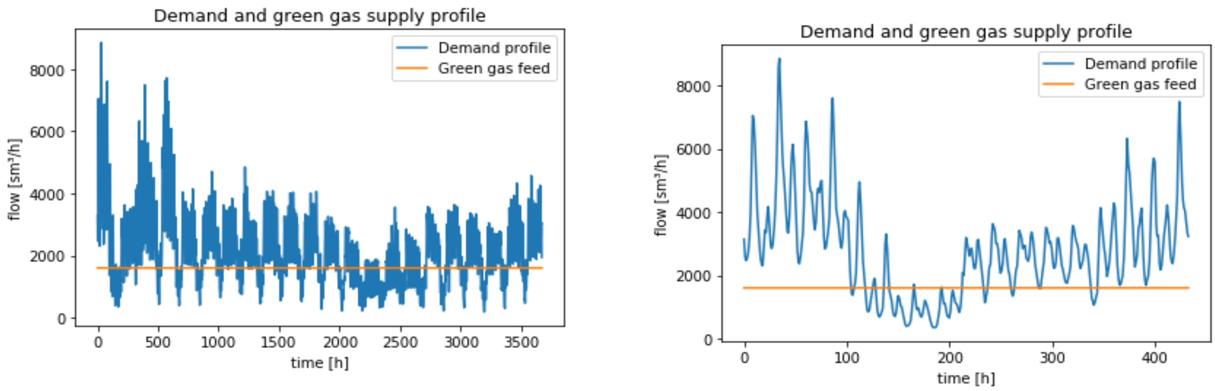
It is important to mention, with the current simulation it is not intended to obtain specific values regarding the storage size or pressure, but to show the possibilities of the model in such that the results could be used as an argumentation for future usage for the distribution network operator to integrate a storage facility within the network. Therefore, the required storage volumes are mentioned in sm^3.

Table 5.14: Required storage volume per solution

Solution [-]	Capacity [m^3/h]	Required storage volume [sm^3]
Static pressure management	1600	573018
Dynamic pressure management	1600	507463

Static pressure management with storage - 1600 m^3/h green gas injection

The gas demand and green gas supply from May to October in Northeast Friesland, the Netherlands is shown in figure 5.23a. As mentioned, the graph does show rather compressed however, looking at the graph, one can notice that at times the green gas supply exceeds the demand and thus injection problems may occur. Figure 5.23b shows the gas demand and green gas supply during the first 400 hours of the simulation period. Clearly it can be seen that during periods of time the green gas supply exceeds the demand.

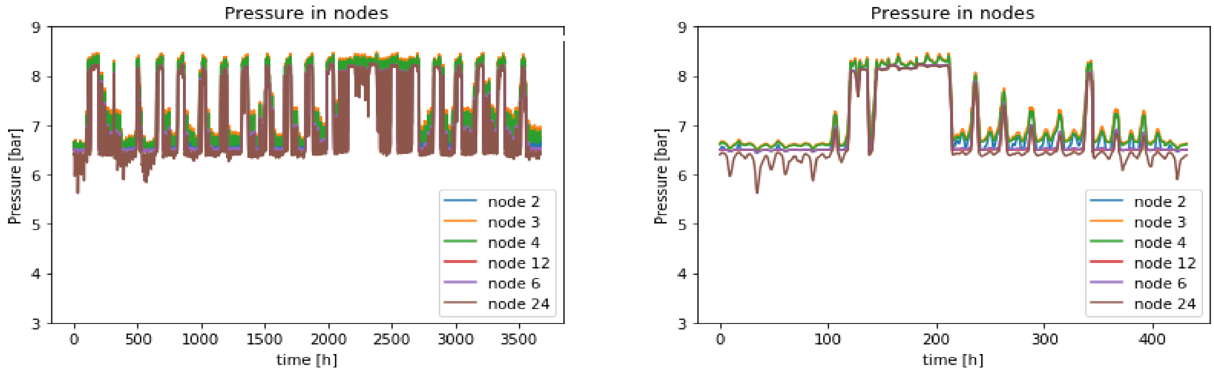


(a) Demand and green gas supply profile from May to October, 2016

(b) 400 hours within the simulation period

Figure 5.23: Demand and green gas supply profile of Northeast Friesland, The Netherlands from May to October, 2016

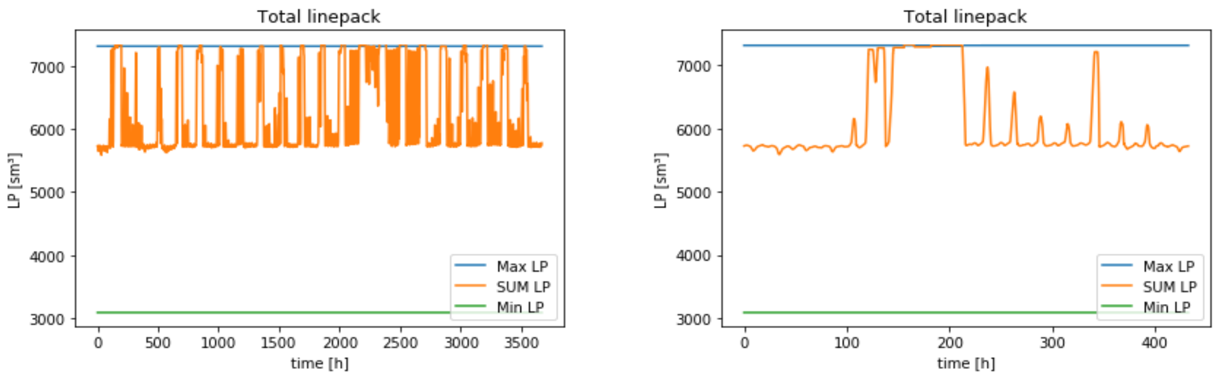
Figure 5.24a shows the pressure course during the simulation period of the gas distribution network in Northeast Friesland. compared with the previous analyses, no remarkable values are obtained.



(a) May to October, 2016 (b) 400 hours within the simulation period

Figure 5.24: Pressure profile of specific points within the gas distribution network in Northeast Friesland, The Netherlands with static pressure management with storage and 1600 m^3/h green gas injection

The linepack within the gas distribution network is shown in figure 5.25. As for the pressure, compared with the previous analyses, no remarkable values are obtained for the linepack.



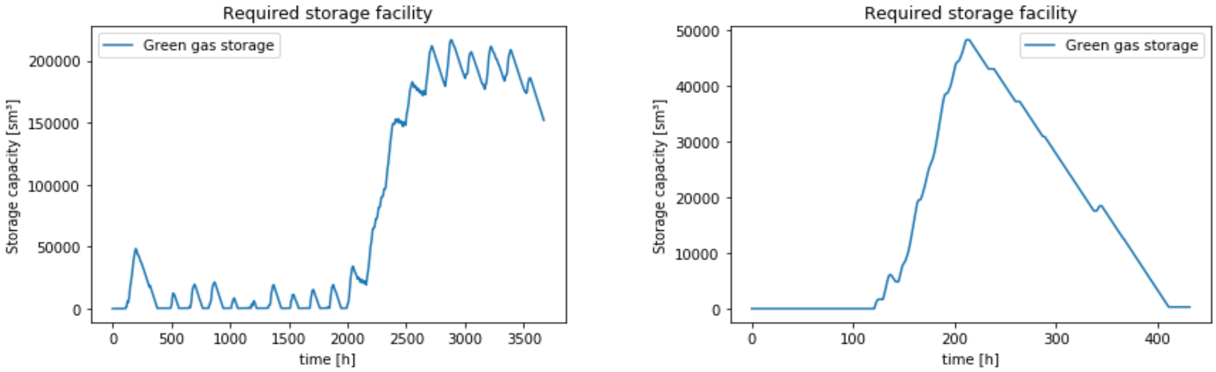
(a) May to October, 2016 (b) 400 hours within the simulation period

Figure 5.25: Linepack within the gas distribution network in Northeast Friesland, The Netherlands with static pressure management and storage with 1600 m^3/h green gas injection

In figure 5.26a, the volume green gas stored within the gas storage facility during the simulation period is shown. Looking at the first 2000 hours of the simulation period, it can be seen that the storage facility is filled and emptied in time. During hours 2000 to 3000 the storage is merely filled, resulting in a maximum storage capacity of $2.2 \cdot 10^5$ sm^3.

It can be seen that, during the simulation period, the storage is not entirely emptied. However, given the fact that the gas demand increases during the winter, and readily exceeds the green gas supply, we can conclude that the storage will be completely emptied during the winter.

Following the results, to inject an average green gas capacity of 1600 m^3/h per year, a storage facility of $2.2 \cdot 10^5$ sm^3 is required.



(a) May to October, 2016

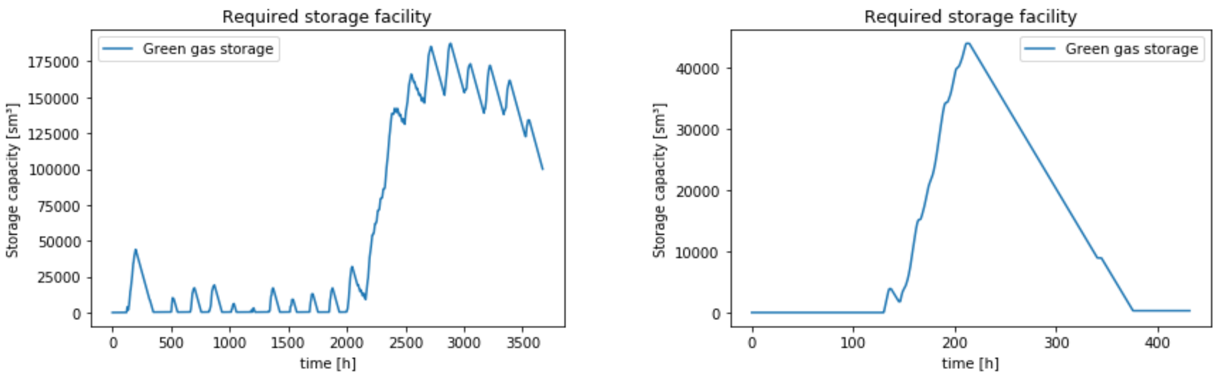
(b) 400 hours within the simulation period

Figure 5.26: Total required size of the green gas storage facility given in sm^3

5.5.2 Capacity increment analysis - Dynamic with storage

Since for the dynamic pressure management with storage similar graphs as for static pressure management with storage are obtained, it was decided to only discuss the results obtained for the storage facility.

Dynamic pressure management with storage - 1600 m^3/h green gas injection
In figure 5.27a, the volume green gas stored in - and injected from - the gas storage facility is shown. Following the results, to inject an average green gas capacity of 1600 m^3/h per year, a storage volume of $1.9 \cdot 10^5$ sm^3 is required.



(a) May to October, 2016

(b) 400 hours within the simulation period

Figure 5.27: Total required size of the green gas storage facility given in sm^3

5.5.3 Conclusion

In table 5.15 the required storage volume of both static- and dynamic pressure management with green gas injection from storage to network is shown. Since within the previous analyses for dynamic pressure management a greater injection capacity was obtained, it is reasonable that for the current simulation with dynamic pressure management less storage volume is required.

With the current simulations it was not intend to obtain specific values regarding the size or pressure but rather to show the possibilities of the model in such, that the obtained results could be used as an argumentation for future usage for the distribution network operator to integrate a storage facility within the network.

Table 5.15: Required storage volume per solution for a yearly average injection capacity of 1600 m^3/h

Solution	Avg. capacity [m^3/h]	Required storage volume [sm^3]
Static pressure management with storage injection	1600	216754
Dynamic pressure management with storage injection	1600	187546

6. Discussion

This chapter highlights a macro view of the developed model wherein we discuss the validity, consequences of different network characteristics, and suggestions for future research.

6.1 Discussion

The study is divided in 4 parts: literature review, the dynamic simulation model, casestudy implementation and validation, and simulations. Within the literature review, the basic knowledge concerning the Dutch gas network, and more in depth knowledge on capacity increment solutions and modelling methods was acquired. In the second part, using the knowledge of the literature study, the model was built and benchmarked against literature literature. Within the process of building the model, assumptions concerning gas temperature, velocity, elevation and compressibility were used. Given the extensiveness of which these assumptions are used within literature, no major deviations were expected for the model which showed to be correct by the validation of the casestudy (third part). Within the fourth part, simulations were performed.

Using the results obtained with the different simulations, Stedin (distribution network operator) is now capable to provide answers to several questions. Questions to which prior to this study no answers could be given. The concerning questions are; the difference in green gas injection capacity between static- and dynamic pressure management, the maximum injectable hours for a given green gas injection capacity per year, and the required size of a storage facility to inject a given green gas injection capacity.

6.1.1 Validity and limitations

An important point of consideration is the understanding of the validity and limitations of the model.

As mentioned in section 5.3, the dynamic pressure management strategy is currently not being exploit by Stedin and no clear system control protocol is known. Therefore, for the development of the model, assumptions to control this strategy are made. Since for the within this study performed simulations we posses over future gas demand data (2016), this data is used within the model to, per timestep, dynamically in- or decrease the city gate stations inlet pressures. Reflecting on real life, since we cannot (exactly) predict the future gas demand, this control system does not fully reflect reality. To accurately describe the inaccuracies obtained from this assumption, first, an actual dynamic pressure management control system should be developed. It could be thought of, in reality, an extra safety margin is added to the city gate station inlet pressure resulting in less green gas injection capacity.

Due to the way green gas suppliers are modelled, there are some limitations to the model. Green gas suppliers are defined by the green gas injection capacity rather than the injection pressure, providing the green gas injection pressure to be a variable obtained by solving the set of equations, Eq. (3.6) and Eq. (3.7). Given that the injection pressure is a variable, instead of a constant, with the current model we are not able to prioritize green gas injection. To clarify, according the law, the first green gas supplier who was connected to the gas distribution network takes precedence on injecting green gas. This precedence is obtained by a difference in green gas injection pressures and thus requires specific set points.

6.1.2 Capacity increasing strategies

In the current study, we focused on the green gas injection capacity increase of static pressure management, dynamic pressure management, and a combination of storage plus pressure management. However, as depicted in figure 1.6, additional strategies for an increased green gas injection capacity exist. Based on the current functioning of the model, referring to the additional capacity increasing strategies, let us discuss the required steps to perform simulations using these strategies.

Connection to local big gas consumers
By the way the dynamic gas network simulation model is build, adding (-or removing) a gas consumer merely requires the location of the big gas consumer (provided with pipe length, diameter) and the hourly gas consumption profile. Using this data - entered in excel - the strategy of adding local big gas consumers to the network is ready to be explored. Therefore, within gas distribution networks wherein this strategy is applicable, this analysis should certainly be performed for determining the green gas injection capacity.

Green gas booster in the distribution network
From a mathematical point of view, the implementation of a green gas booster requires similar steps as connecting a big gas consumer, except for one criterion. Whereas for a big gas consumer the gas consumption profile is known, a green gas booster compresses the green gas excess from the distribution network into the regional transmission lines, for which the hourly excess green gas is an unknown. Following this, the implementation of a green gas booster requires an extra constraint within the model ensuring the green gas excess to be withdrawn and compressed into the regional transmission lines. By enabling the model to simulate a green gas booster station, the dynamic gas network simulation model can be used to determine the best location for the placement of a green gas booster. Here, the best location is defined as the location at which the lowest pressure drop occur.

Connect different distribution networks
Although within this study the connection of different gas distribution networks was not analysed, the model does offer the ability. In order to perform analyses on the green gas injection capacity, for when different gas distribution networks are coupled, first different (separate) gas distribution networks should be extracted from Irene Pro and implemented within the model, section 4.1. Hereafter, the two - or more - separate gas distribution networks can be connected via a pipeline and analyses can be performed.

6.1.3 Network characteristics

The current study merely focused on one gas distribution network. Within this section, the impact of network characteristics on the green gas injection capacity are highlighted.

One of the properties which determine the green gas injection capacity is the total volume of the network. As discussed in section 2.2.1, linepack is a function of the geometry of a network (volume), the difference in allowed lower- and upper limit pressure, and gas characteristics. In essence, an increased total network volume results in a greater linepack flexibility and thus, more green gas injection capacity. However, for this to be valid, note should be taken on the topology of the network. The influence of the network topology on the green gas injection capacity is clarified by means of an example.

Given are the gas distribution networks depicted in figure 6.1. Let us assume, except for the furthest point measured from the city gate station (endline) and the total network volume, both networks are identical with identical gas demand profiles. The gas distribution network depicted left has, compared to the gas distribution network right, a larger volume and a greater distance is measured from city gate station to endline. Now, without using specific values, the following two scenarios can be thought of. In the first scenario, we assume the endline consumer depicted in the left network to represent a single household. For the second scenario, we assume the endline consumer depicted in the left network to represent industry, Resp. low and high gas consumption.

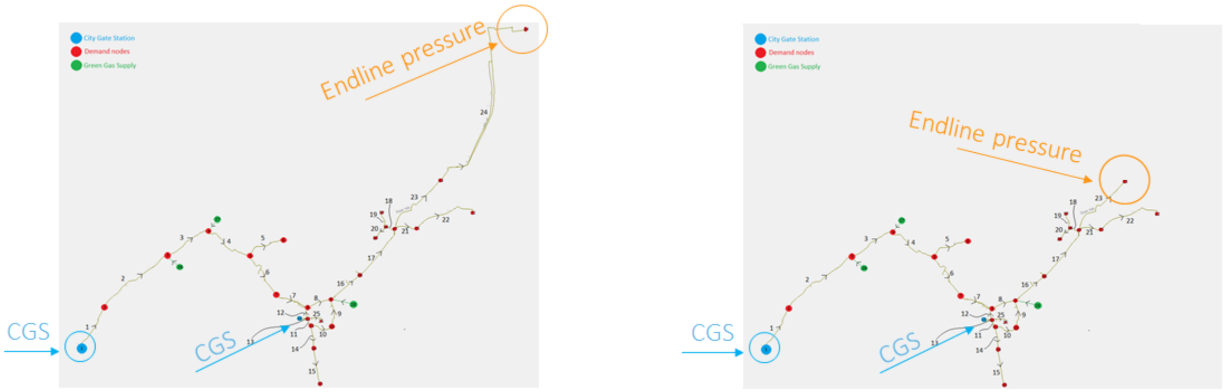


Figure 6.1: Two gas distribution networks differing in total volume and furthest point measured from the city gate station

Looking at scenario one, because of the low gas consumption profile, the pressure drop within the left gas network will not differ much with the pressure drop within the right network. Thus, because of the larger network volume, and similar pressure drops, the left gas network will have a higher green gas injection capacity.

If we have a look at scenario two, because of the high gas consumption profile, the pressure drop within the network depicted left is much higher compared to the pressure drop within the network right. As a consequence of this higher pressure drop, in order to fulfil the lower limit boundary condition, the city gate station inlet pressure should be set higher resulting in an on average higher pressure within the network, and less green gas injection capacity.

6.1.4 Study expansion

Together with KIWA, Stedin investigated whether the Dutch village Stad aan 't Haringvliet can switch from natural gas to green hydrogen. Using the existing natural gas network, the hydrogen can be transported and, according the study, in 2025 the city could be completely switched over to green hydrogen. However, provided the right adjustments (Stedin & KIWA, 2019).

During the course of this study, great interest in using the dynamic gas network simulation model for the study to switch 'Stad aan 't Haringvliet' from natural gas to green hydrogen was found. The writer shares this interest and wants to emphasize that, by using the model, dynamic insight regarding the pressure, pressure drop, and capacities can be obtained. A criterion to ensure the supply of green hydrogen throughout the network, in all circumstances.

Given this potential, performing another (small) study in which the model is adjusted for the simulation of green hydrogen within the natural gas network of 'Stad aan 't Haringvliet' would be highly beneficial.

7. Conclusions

This chapter discusses the obtained results and provide further model improvements and recommendations.

7.1 Conclusion

Within this study, several green gas injection capacity increasing solutions are explored, to obtain the capacity per solution. The main objective of the study was to:

Provide a substantiated answer on the capacity increase of green gas injection within the Dutch gas distribution network, as a consequence of capacity increasing solutions- or a combination of solutions.

To provide an answer to the main objective, a dynamic gas network simulation model was developed. The development of this model required the modelling of several components, such as generic input tables in which the network characteristics can be entered to assemble the gas distribution network within Python. Providing this generic input tables, the user has the ability to easily perform analyses with different gas distribution networks.

The validation of the dynamic gas network simulation model was performed according two methods. Within the first method, the outcomes of the model were compared with results obtained from literature. In the second method, a casestudy network was implemented of which the results were compared with the results obtained from the commercialized steady state gas network calculation program Irene Pro.

In the model, the dynamics of gas transport along pipes are described by a combination of the isothermal Euler equations and the real gas law. For describing the network characteristics, an incidence matrix was used. By combining this incidence matrix with boundary conditions, and the hourly green gas supply and demand data, the gas distribution network is assembled which is solved iteratively. After solving the set of equations, insight in network pressure, flow, flow direction, linepack, and green gas injection capacity is obtained.

The combination of the total network volume, the lower- and upper limit pressure boundary condition, the topology of the network, and the hourly gas demand were found to affect the green gas injection capacity the most. Given that one property may affect the other, it cannot be said that an increased total network volume directly results in an increased green gas injection capacity. For instance, an increased total network volume may result in a higher pressure drop, requiring a higher city gate station inlet pressure and thus, less green gas injection capacity.

Following the results of this study, it can be concluded that dynamic pressure management results in a greater green gas injection capacity compared to static pressure management, due to the difference in city gate station inlet pressures. Where for static pressure management the city gate station inlet pressure is changed manually, and a safety margin is required, dynamic pressure management is done automatically providing the possibility to inject with a lower city gate station inlet pressure. The required city gate station inlet pressure, for different gas demand scenarios, is obtained with the model. Using this data, the distribution network operator can make substantiated decisions on when to change the city gate station inlet pressures for the exploitation of static pressure management. Besides the pressure management strategies, the use of a storage facility was analysed. Following the outcomes of the model, per green gas injection capacity, the required storage size is obtained.

By aggregating the results obtained with the simulations of both pressure management strategies, the green gas injection capacities were plotted against the total injectable hours per year. Using this graph, the distribution network operator is able to directly attain the potential green gas injection capacity with its corresponding injectable hours per year. By providing this data to the distribution network operator, a direct response on enquiries from green gas suppliers can be given resulting in a more successful settlement of green gas feed in requests.

7.2 Model improvements and recommendations

For the current model, as a consequence of data availability, the gas demand profile of all separate gas consumers was lumped together to several different gas demand nodes. Here, each node consumes a percentage of the total amount of gas injected into the network. Since in reality not all consumers have the same gas consumption profiles, for future improvements, per demand node a more realistic gas consumption profile should be assigned to obtain more accurate results. A possible approach for obtaining this improvement, is the integration of a new model in which the gas demand profile of specific nodes are based on variables as family composition, living area, temperature, and time. For example, in a study performed by (Farzaneh-Gord & Rahbari, 2018), the gas consumption profile was modelled based on the outside temperature. By expanding the within (Farzaneh-Gord & Rahbari, 2018) developed gas consumption profile to one in which family composition and living area are taken into account, and combining this with the model developed within the current study, even more accurate results could be obtained.

During the course of the study, it was found that the topic of using renewable gasses (green gas and green hydrogen) within the gas distribution network is frequently discussed by different parties. However, despite the attention, up to now there were no insights into the dynamic course of pressures and flow within a network. Given that with the current model these insights are provided for green gas usage, expanding the model with the ability to apply green hydrogen would be very beneficial.

To finalize, given the importance of economics, it is advised to conduct a study focusing on investment cost. Within this study, variables as the total green gas potential of a specified area should be estimated in order to make substantiated decisions whether to invest in which solution, taking into account the future green gas injection potential.

A. Appendices

A.1 Network properties casestudy network Northeast Friesland, The Netherlands

The gas distribution network properties of the casestudy network in Northeast Friesland are shown in table A.1. Within the first column, the node number is given. The second column provides the pipe number, and the third and fourth column provide the different pipe lengths and diameters.

Table A.1: Pipe properties simplified gas distribution network Northeast Friesland, The Netherlands

Node [-]	Pipe [-]	Length [m]	Diameter [m]
1	1	3003	0,15
2	2	5073	0,1008
3	3	3059	0,1008
4	4	3389	0,1008
5	5	2390	0,1008
6	6	3644	0,15
7	7	2164	0,2073
8	8	1601	0,2073
9	9	1777	0,2073
10	10	1518	0,2073
11	11	440	0,2073
12	12	675	0,2073
13	13	400	0,2073
14	14	1375	0,2101
15	15	2263	0,2101
16	16	2380	0,15
17	17	3317	0,15
18	18	584	0,1008
19	19	948	0,1008
20	20	1016	0,0531
21	21	1493	0,1008
22	22	4120	0,09
23	23	4643	0,1008
24	24	13798	0,1008
25	25	1070	0,1008

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