The future of L gas in North West Europe

Using Linear Programming to assess the future robustness of the North West European L gas system under the decline of Groningen production capacity

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(Public version)

Using Linear Programming to assess the future robustness of the North West European L gas system under the decline of Groningen production capacity

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I hope you enjoy reading this thesis.

Jon Bijl

Delft, October 2012
Executive summary

The L gas system in North West Europe is facing the challenge of handling the production decline of the Groningen gas reserve, the main source of L gas in North West Europe. With about 70% of the L gas in this system produced from the Groningen field, this future decline has put down questions about the ability of this system to maintain the balance between demand and supply on the long term. The other 30% of the L gas in NWE is produced in Germany, in smaller fields within the Netherlands or produced as H gas and converted to L gas with nitrogen. This physical system of production locations, underground gas storages, blending stations, quality conversion facilities, pipelines and demand nodes delivers gas to households in the Netherlands and parts of Germany, Belgium and France.

Within the NWE L gas system there are multiple stakeholders active with different interests regarding gas quality in general and in specific the functioning of the L gas system. The Dutch government has two important public values that are potentially influenced by the decline in production capacity: a safe and reliable supply of gas for its inhabitants and the optimal utilization of Dutch gas reserves. Natural gas represents 5% of total state income.

In this research, Linear Programming has been used with the objective of creating a workable and accessible simulation tool to evaluate the physical flows within the L gas system until 2030. Current modeling approaches used within the industry are either too simplistic or too complex to evaluate the development of the L gas system over a time period of 20 years while capturing its many complexities. A merit order of sources has been designed, with virtual costs assigned according to this merit order. The total costs of the gas system are then minimized, under the technical constraints within the system. The system constraints are limited to demand constraints, production constraints, storage constraints, quality constraints and by constraints from the existence of physical connections in order to maintain the workability of the tool. This tool is modeled in modeling software Linny-R, developed at the TU Delft. This has provided an attractive interface to easily implement system constraints or to adjust values within these constraints.

Installing extra nitrogen production capacity, a transition of L gas grids into H gas grids and increased storage capacity have been identified as the three main options to maintain the ability of the L gas system to provide for the L gas demand in the next 20 years. 5 different patterns of transition combined with extra nitrogen capacity as a policy response have been simulated against 4 demand profiles. In the 4 demand profiles, gas demand is split up mathematically into temperature related demand and temperature unrelated demand. Combining 5 policy responses and 4 demand profiles has led to 20 scenarios that have been simulated in the simulation model of the physical L gas system.

Based on the modeling assumptions, it appears that extra nitrogen production capacity is not needed before 2025, but that the need for extra nitrogen production capacity is high from this year onwards if there would have
been no transition of grids at all. Production in Groningen will change from a flexible swing field into a base load producing field from 2020 onwards, thereby leaving its function as the main source of flexibility blank. H gas is the only source that can fill in this gap. Therefore, the demand for H gas capacity will increase, both in terms of total volumes and in peak capacity. This increase will start from 2015 onwards. The flexibility of H gas delivery should either be delivered by flexible import contracts or by increased H gas storage capacity. The exact demand for H gas storage capacity should be evaluated into more detail but it is recommended for EBN to look into this.

In order to control the investment costs for extra nitrogen capacity, a transition of L grids should start from 2022 onwards, either in a fast pace in the L gas importing countries, or in a relatively slow pace in the entire system, including the Dutch grid. Neither one of these two is accounted for in the TSO plans at this time. Considering the costly, time consuming and complex process of this transition, the stakeholders involved should be notified in time of the planning of this transition in order to control this process towards a satisfactorily speed and order. As the objectives for all parties involved appear to be aligned, transparency would improve the ability to control this process. As Groningen off take is guaranteed in all simulated scenarios, the fear of losing market for L gas should not be a reason to avoid this transparency.

Based upon the assumptions in my scenario’s and model, in order to protect the public values for the Dutch government, the most favorable alternative would be to postpone the transition of the Dutch grid until 2030. The necessary investment in nitrogen capacity is moderate, with capital costs between €60 million and €300 million and additional operational costs of €80 million to €160 million per year at its peak. However, these costs are more than outweighed by the extra income from Groningen gas, largely beneficial for the Dutch society, and the costs efficiencies of a delayed transition of grids. This would also avoid the return of a quality label on TTF, which is important for the ambition of TTF to be a leading hub in Europe.

If a transition of grids within the Netherlands is decided, it is recommended that the Dutch government takes up a leading and coordinating role. The transition of L gas grids to H gas grids is a delicate process that needs close cooperation of all parties involved. The safety risks are high and the operation is typically executed in areas with a lot of houses. Also, there is no incentive for DSOs to take the first steps as the costs of a transition decrease rapidly over time. Therefore, it is important to control and monitor this process. The Dutch government should take a coordinating role in this process in order to safeguard its safety.

**Linear Optimization to simulate flows in a natural gas network**

Linear Optimization appeared to be a good method for a workable and accessible simulation tool for physical flows within a general natural gas system. The shortcomings of more simplistic methods were overcome while maintaining an acceptable running time and an attractive and understandable model. The main shortcomings of more simplistic methods that were overcome were:

- Place independency; more simplistic methods aggregate all components per function
- Allowance for quality ranges; more simplistic methods assume one static quality

- Use of time series; more simplistic methods ignore fluctuations in demand

Shortcomings to the method used in this research are that the hourly fluctuations in demand against the seasonal fluctuations of storages make that a large look-ahead time needs to be used in the model, thereby decreasing the speed of the simulation tool and therewith the workability of this tool. This was compensated for by auxiliary constraints to be able to use a smaller time step. Subsequently, these auxiliary constraints reduced the accessibility of the model for third parties.

Secondly, LP can only be used to simulate the flows within a system if this system is used optimally. Therefore, simulating the flows within a natural gas system with LP should always be used in combination with a more qualitative analysis of stakeholder behavior within the system in order to put the outcomes of the model in the right behavioral perspective.

The simulation tool in this research has been positioned in between the single point analysis and the complex planning models used by TSO's. It should be considered case by case what modeling approach fits the requirements. This research has set the first step in the development of a modeling approach that goes further than the single point analysis, but that is still workable in such a way that it can be used to model over a long period of time with different scenarios. This is a relevant contribution to the long list of mathematical optimization methods as used for natural gas systems.
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1 Introduction

In 1959, the giant natural gas reserve in Slochteren, Groningen was discovered in the Netherlands. This gas field appeared to be unique, not only because of its massive initial reserves, but also because of the composition of its gas (Correljé and Odell 2000). The calorific value was lower compared to most of the smaller fields within the Netherlands and also compared to the gas imports from Russia and Norway. In the North West European transmission networks the following gas quality types are identified (Gasterra 2012):

- **L gas**. Gas with a relatively low calorific value. This gas has a low calorific value because it is not only composed of hydrocarbons, but it also has a large content (up to 25%) of nitrogen and/or CO$_2$. Gasses with a Wobbe index$^1$ of 42.5 – 47 MJ/m$^3$.

- **H gas**. Gas with a relatively high calorific value. This gas is mainly composed of hydrocarbons. Gasses with a Wobbe index of 48 – 56 MJ/m$^3$.

- **G-gas**. G-gas (Groningen-gas) is the term used for the gas from the large gas field in Groningen. It is composed of methane (81%), higher hydrocarbons (3.6%), sulphide (H$_2$S) (0.4%), and for the other 15% of nitrogen and CO$_2$. G-gas provides on average 35.17 MJ/m$^3$. This equals 9.8 kWh. Its Wobbe index is 43.8 MJ/m$^3$. Therefore, it is within the quality range for L gas.

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$^1$ Wobbe-index. The Wobbe-index is a measure of the combustion velocity of the gas, which is calculated by dividing the heating value of the gas with the square root of the relative density. The Wobbe index is a measure for the amount of energy that flows through a burner per time unit. As this determines the required amount of oxygen to totally burn a gas flow this parameter is the most important parameter when assessing the interchangeability of two distinct gasses in a gas network.
Because of this large difference in gas quality, two separate gas infrastructures operate next to each other: One network transporting and delivering H gas and one network transporting and delivering L gas. If not mentioned otherwise, this research uses the Groningen Equivalent ($n; 35.17 \text{ MJ/m}^3$) of a natural gas when describing its volume.

1.1 Future decline in L gas supply

The main source within the L gas system, the Groningen gas field, has been producing gas since the 1960s. Although its current reserve is still enormous, around 900 bcm (EL&I 2011), the rate at which this gas can be produced is declining (Visser 2011). Earlier depletion of the gas field has reduced the natural pressure within the field, which was the main reason for its initial high production capacity and production flexibility (Mulder and Zwart 2006). This production capacity will reduce further when more gas is being extracted. The estimated production of the Groningen field is shown in Figure 1.2.

![Figure 1.2 Estimated Groningen production per year and production capacity based on public data (EL&I 2011; Visser 2011)](image)

From this figure, it can be seen that in the coming years, the maximum production capacity per day decreases first, whereas the total yearly volumes produced remain constant. After 2022, the total yearly volumes are expected to decline too.

The secondary source of L gas in North West Europe is gas produced in Germany. These sources are expected to decline, as can be seen in Figure 1.3.
From figure 1.2 and figure 1.3, it is clear that the total supply of L gas in North West Europe will decline in the coming years. However, there is uncertainty among stakeholders what the impact of this decline will be on the functioning of the L gas system, the technical system that transports L gas and delivers it to its consumers. The uncertainty derives from the complexity of a natural gas system in general, and the North West European L gas system in particular, which makes it difficult to predict how this system will evolve. A natural gas system can be seen as a socio technical system (Correljé 2012). In such a system, two ways of complexity exist: Technical-physical complexity and Social-political complexity (Herder and de Bruin 2009).

Technical-physical complexity within the L gas system becomes apparent in uncertainty about the magnitude of the decline in L gas production, and the impact of this decline to the functioning of the system. Groningen production data is commercially sensitive information and not openly available. Therefore, different estimates about this decline exist in literature (Mulder and Zwart 2006; CREG 2010; Visser 2011). Also, the demand for L gas and the way that this demand will evolve is uncertain. Finally, the complex functioning of a natural gas system makes it hard to predict the physical boundaries of a natural gas system. This complexity results in different views among stakeholders about the impact of this Groningen decline on the functioning of the L gas system. However, it is clear that the decline of Groningen production is significant and that this will impact the L gas system in some way. The main questions about this decline regard the impact and the timing of this impact.

Social-political complexity becomes apparent in uncertainty about stakeholder behavior within the L gas system. A number of technical solutions are known that potentially mitigate the impact of the decline in Groningen production capacity. These solutions are to be implemented by different stakeholders and there is uncertainty within the market if, when and how these technical solutions are to be implemented. The timing of these investments will impact the flows in the system and therewith the benefits to the stakeholders involved. In order
to evaluate the impact of the decline of L gas supply it is important to gain insight in the way that these investments decisions are made and in the main drivers behind these decisions.

### 1.2 Historic policy responses

The future decline of Groningen production capacity has been known for years and this has already led to different policy responses to control the impact of this decline. In 2006, a “production cap” was included in the Dutch “Gaswet”, the natural gas law (Mulder and Zwart 2006). The objective of this production cap was to avoid a too rapid excavation of the Groningen field. Based on this cap, NAM (the operator of the Groningen field) was allowed to produce no more than 425 billion cubic meters (bcm) in the period 2006-2015.

In 2010, a new production cap was set at 425 bcm for the period 2011-2020. In addition to this an extra 21 bcm was allowed to be produced within the first 5 years, as this was still remaining from the first production cap. This gives a total of 234 bcm for the period 2011-2015, or on average 46,7 bcm per year, and a total of 212,5 bcm for the period 2016-2020 (on average 42,5 bcm per year) (Rijksoverheid 2012).

In 2010, the Dutch government responded to the change in gas quality within its networks by launching the website [www.hoezoandergas.nl](http://www.hoezoandergas.nl), a website that explains the consequences of different gas qualities in the Dutch gas infrastructures. On this website, plans for a quick implementation of a larger Wobbe range were introduced. Also, the Ministry of Economic Affairs commissioned a research to Kema and Kiwa. This report called “Gaskwaliteit voor de toekomst” (translation: “Gas quality for the future”), presented the implications for a larger Wobbe range and also made estimations about the costs of converting L cal grids in the Netherlands to H cal grids (see table 2.2). A reason to explore the costs of this transition would be a situation in which there is not enough L gas to provide for the total L gas demand in the future.

<table>
<thead>
<tr>
<th>Year</th>
<th>Costs of transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>€ 2.6 – 5.7 billion</td>
</tr>
<tr>
<td>2025</td>
<td>€ 2.7 – 2.8 billion</td>
</tr>
<tr>
<td>2030</td>
<td>€ 0.6 – 0.7 billion</td>
</tr>
</tbody>
</table>

Table 2.2 Costs of a transition in the Netherlands according to Kema and Kiwa’s “Gaskwaliteit voor de Toekomst”

Based on this report, it was decided in a ‘kamerbrief’ (letter to the Dutch parliament) by the Ministry of Economic Affairs that the quality for L gas was to be maintained until at least 2022 in order to avoid the high costs of changing this quality on the short term. EDGaR, Energy Delta Gas Research, was commissioned to investigate whether this quality could technically be maintained even longer in order to reduce costs even more. Also, it was proposed that the new quality specifications for the period thereafter would be set (EL&I 2011).

In 2011, a consultation convention with all stakeholders involved was organized. The preceding reports and decisions had evoked attention among manufacturers of gas burning appliances, who were not involved in the
process before. They criticized the large Wobbe range for the new specifications and the relatively short time span of 10 years because it would lead to dangerous situations for their customers as they argued (FIGO 2011).

The political responses for Germany, Belgium and France are discussed extensively in Chapter 6.

1.3 Natural gas policy objectives within the Netherlands

This research is written from the perspective of the Dutch government as the problem owner. In particular, the Dutch ministry of Economic Affairs (EL&I) is responsible for the exploitation of the Dutch natural resources. Ever since the discovery of the Slochteren field, natural gas production has been an important subject in Dutch politics. Correljé and De Vries (2010) have distinguished four main policy objectives for the Dutch government regarding natural gas:

- Payable gas supply
- Reliable gas supply
- Clean gas supply
- Optimal utilization of Dutch gas reserves

The decline in Groningen production mainly affects two of these four policy objectives: the reliability of natural gas within the Netherlands and the optimal utilization of reserves.

1.3.1 Optimal Utilization of Dutch gas reserves

The Netherlands has benefited greatly from its position as one of the main gas producing countries in North West Europe. In the period 1959-2011, the total income to the Dutch government from natural gas was €236 billion (Aardgas in Nederland 2012). In the total state budget for 2013, the income from natural gas is budgeted at €12,1 billion, accounting for 5% of the total State income (Rijksoverheid 2011).
The Groningen gas, being produced in the biggest gas field, contributes significantly to this large amount of State income. Large volumes or Groningen gas are exported to Belgium, France and Germany, bringing in money for the Dutch government. The money flows directly to the state via EBN, and indirectly via taxes on gas sales, for example corporate income tax. Specifically for the Groningen field, the “Meer Opbrengst Regeling (MOR)” (lit translation: More Revenue Arrangement) has been set. By this arrangement, 85% to 95% of the extra revenues of the Groningen gas sales are paid to the Dutch government (EL&I 2008). With this financial arrangement in mind, it is clear that the remaining 900bcm in the Groningen field in combination with an average gas price of roughly €0.25/m$^3$ represent a large value for the Dutch government. In order to maximize the value from this field, the demand for this gas is to be maintained. With the uncertainty among stakeholders about the technical capability of the L gas system to provide for enough L gas, this demand might decline if consumers would substitute L gas by other energy sources. For the Dutch government it is important to avoid this diversifying behavior towards substitutes among the stakeholders involved at a too early stage in order to maximize the value of the remaining reserves in Groningen.

1.3.2 Reliable supply of gas

A second important value for the Dutch government regarding natural gas is gas as a reliable source of energy. This reliability concerns both the safety of gas and the security of supply of gas. As all households and many industrial consumers rely in their daily operation on L gas supply, this reliability is an important public value that
the Dutch government should protect. Physical supply and demand of L gas need to be in balance all the time. Besides incidental disruptions because of force majeure, a structural deficit of L gas to provide for demand should be avoided. Secondly, if Groningen gas is to be replaced by other sources of natural gas, the quality of these gasses can differ. Changing the gas quality used for gas burning appliances potentially result in safety risks.

Concluding the preceding, insufficient supply of L gas would lead to the undesirable situation in which households and industry could be disrupted in their gas supply. Insufficient demand would lead to a surplus of L gas that would either have to be sold at a lower price or at a later point in time, thereby decreasing the real value of gas (taking into account the time value of money), while insufficient supply would lead to reliability issues. Thus, it can be stated that balancing supply and demand of L gas is essential in order to safeguard these two important values for the Dutch government.

1.4 Problem statement and research objectives

Concluding the preceding, the L gas system in North West European will experience changes in the coming 15 to 20 years, driven by the decline in Groningen production capacity. There is a need within the industry to have a clear view on how this system will evolve, in order to safeguard the optimal utilization of Dutch resources and a reliable gas supply. Based on this, the following central problem statement is formulated:

Problem statement:

*With the future decline in L gas supply, there is uncertainty in the North West European L gas market about the future balance between demand and supply, which might lead to diversifying behavior on the demand side.*

This problem is driven by two main uncertainties: uncertainty about the technical capabilities of the L gas system to continuously supply the market with sufficient L gas and uncertainty about the behavior of stakeholders towards technical solutions to mitigate the impact of the decline in Groningen. This behavior can be diversifying in two ways: Diversifying as stakeholders in different countries and with different interests might respond differently compared to other stakeholders and diversifying as consumers might tend to diversify to other gas qualities for their supply.

In order to maximize the utilization of Dutch natural gas resources and to maintain a reliable supply of L gas, it is key to get a better insight in the mechanisms that play a role in the L gas system. These two components are described in two different needs within the system, derived from the technical-physical complexity and the socio-political complexity in a socio-technical system:

1.4.1 Need for an accessible simulation tool that handles the systems’ complexity

Within the industry, many parties have been active in analyzing the future capacity of the L gas system. Most of the times, a single point analysis has been used that evaluates the peak capacity of the system using a Load
Although the single point analysis is a good method to quickly compare capacities and demand, it does not account for many complexities and interdependencies within the North West European L gas system because of a number of reasons. These reasons are partly discussed in the CIEP report; other reasons, mainly regarding gas quality, are specifically relevant for the L gas system. The 3 main reasons are:

- Single point analysis is place independent; all components are aggregated per function
- Single point analysis does not allow for quality ranges; it assumes one static quality
- Single point analysis does not make use of time series, thereby ignoring fluctuations in demand in time

In a single point analysis, all gas system functions are aggregated into one capacity, which does not account for the interaction between the different system components. Locations of the single components have not been taken into account in this approach. Also the range within the quality specifications is not included in this modeling method. It assumes one static quality, while in the real system the gas quality can vary between the upper bounds and the lower bounds. Finally, the single point analysis does not make use of time series and therefore it does not account for the patterns of demand in terms of accumulated production and between-day differences in demand.

GTS, the operator of the Dutch transmission grid, has designed a planning tool that takes many of these complexities into account. This tool is focused on calculating the exact situation within the grid, including the exact pressures and other technical components within every single pipeline. Because of this high level of detail, this simulation tool is not designed for the long term simulations that are necessary for this problem statement. The running time would be too large, and it cannot be easily adjusted to see the effects of different stakeholder decisions. Also, the model is very complicated and therefore very hard to understand, to use and to interpret the results.

Thus, stakeholders are interested in a more detailed simulation tool that covers for the weaknesses of their single point analysis but that can be easily understood, that can easily be adjusted to changing system parameters and that runs quickly enough to simulate a long period of time. Before this research, such a model was not used among the stakeholders associated with the North West European L gas system. This model should be able to answer the following questions:

1. What is the effect of declining production capacities to the technical ability of the system to provide for the demand for L gas? Will an imbalance between demand and supply appear, and if so, on what term?
2. How will different investment options of stakeholders influence the physical flows within the L gas system?

3. How will changing parameters within the system affect the utilization of the Groningen field, storage facilities and conversion facilities?

1.4.2 Need for an understanding of investment options and stakeholders’ decision criteria

With the different interests within the L gas system for the stakeholders involved, there is no clear view about the occurrence of investments, about the way that these investment decisions are made and about the consequences of those investments for the interests of the different stakeholders involved. Understanding the converging interests within the system and the way that these interests influence the behavior of the stakeholders associated with the system will help determining a company’s position towards market developments.

1.5 Research questions

Based on the research objectives formulated in the preceding chapter, the main research question is formulated:

**What scenarios can be designed for the L gas market and how is the physical balance between demand and supply maintained by stakeholders’ investment decisions in these scenarios?**

Central in the problem statement is maintaining the physical balance between demand and supply. This physical balance is influenced by the boundaries of the system to provide the gas and to transport it to the right locations and by stakeholder behavior within this system.

In the preliminary analysis it appeared that the current simulation methods for monitoring this balance do not sufficiently balance complexity and workability. Existing models are either too complicated and therefore not workable, or too simplistic and therefore missing important facets of a gas infrastructure. The use of a workable model that covers more of the complexities within the system would clarify on the impact and the timing of a potential imbalance and on the impact of alternatives on the ability of the system to maintain this balance. Therefore, the scientific question related to this research question is:

**What method can be used to simulate the flows within a natural gas system in a workable and accessible model? How satisfactorily is this method and what are shortcomings to this method compared to existing models?**

These two main research questions are answered by answering the following sub questions, divided in 4 phases.

**General functioning of the L gas system.**

1. What are the main characteristics of the L gas system and how is it operated?

2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality?
Quantitative analysis of the physical balance between supply and demand.

3. What are the requirements and objectives for the modeling approach?
4. What modeling technique can be used to reach these objectives?
5. How is this general modeling technique applied to the NWE L gas system?

Qualitative analysis of stakeholder preferences.

6. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation?
7. What are the preferences of stakeholders towards these solutions?
8. What are the KPI in the L gas system and how would stakeholders respond to changing KPI?

Integration.

9. What possible future scenarios for the L gas system can be designed?
10. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond?
11. How is the physical balance between supply and demand expected to evolve in these scenarios?
12. To what extend did the chosen modeling technique meet initial requirements?

1.6 EBN and its objectives

This research is executed under the supervision of EBN, who represents 40% government share of the Groningen field. The remaining reserves in the Groningen field are of great value, and the exploitation of these reserves is important to EBN. EBN has noticed that different stakeholders could perhaps tend to different solutions and it wants to sharpen its view as in what direction the L gas system is developing. For EBN it is important to maintain the demand for the amount of L gas it can produce in the long term. In that sense it is important to avoid a mismatch between supply and demand as it would disrupt the market, but also to avoid a too quick or a too drastic transition from L gas networks to H gas networks as it would limit the demand for their gas. Therefore, timing is essential. It is convinced that the stakes are too high for the stakeholders involved for a mismatch to actually appear. However, the actual way that this mismatch is avoided impacts the interests of EBN.

By commissioning this research, EBN wants to explore future scenarios for the L gas market and the consequences of these scenarios for EBN. In these scenarios, it wants to know at what points in time decisions can be made by what stakeholders, and what the effects of these decisions would be. Also, it wants to have a better picture of the interests and motivations of stakeholders regarding the L gas market.
1.7 Research Outline and methodology

This thesis presents the results of the research described above. Throughout this research, a number of interviews have been conducted at 14 different organizations. These interviews have been very helpful in understanding the market mechanisms, getting a better understanding of the different roles and the different interests within the market and in the validation phase of the simulation model. The list of organizations that is interviewed is presented in Appendix A.

In figure 1.5, the structure of this thesis is presented. The sub questions are divided into 4 distinct research phases.

In the first phase, the background of the North West European gas market will be sketched. The results of this phase are presented in chapter 2. This understanding will be the backbone of the research as it uses the history of natural gas systems in NWE to clarify on the current environment of the L gas system. This phase sets the definitions, institutions, stakeholders and technologies for the rest of this research.

The second phase covers the technical-physical complexity of the system. A quantitative model will be designed to simulate the flows within the L gas system. In chapter 3, Linear Programming is introduced as a means to simulate the flows within a natural gas system in general. The constraints and main assumptions are specifically applied to the L gas system in North West Europe in chapter 4. Chapter 5 describes how this general LP problem is implemented into modeling software.

Chapter 6 presents the results of the third research phase, enhancing the socio-political complexity of the system. The technical alternatives that are considered to mitigate the problem of the declining production capacity are introduced. Also, the stakeholder preferences regarding these alternatives are discussed. This forms the basis for the qualitative evaluation of the model outcomes. Finally, the relevant system performance indicators that need to be evaluated quantitatively by the simulation tool are determined.

The fourth phase integrates the first three phases into an integrated analysis of the future of the L gas system. Chapter 7 translates the alternatives discussed in Chapter 6 into 5 different Policy responses. Combining these 5 policy responses with 4 demand profiles results in 20 possible future scenarios, which are evaluated throughout the research. These scenarios are implemented in the simulation tool to assess the impact of these policy responses to the functioning of the L gas system in chapter 8 and chapter 9. These two chapters present the answer to the main research question.

Chapter 10 reflects on the use of Linear Optimization as a means to simulate the flows in a general gas infrastructure. It assesses to what extent the modeling objectives are met and the modeling questions are answered. This chapter concludes on the scientific research question in this thesis. In chapter 11, all conclusions are recaptured in a systematic way and translated into recommendations for the L gas stakeholders in general and to the Dutch government and EBN in particular.
Phase 1 Background: General functioning L gas system

**Input**
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH2)

**Output**
1. Concepts and definitions natural gas systems (CH2)
2. Basic understanding L gas system (CH2)
3. Main stakeholders and interests regarding gas quality (CH2)

Phase 2 Modeling

**Input**
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach these objectives? (CH3)
3. How is this general modeling technique applied to the NWE L gas system? (CH4,5)

**Output**
1. General modelling approach (CH4)
2. Merit order of supply sources (CH4)
3. Main system constraints (CH4)
4. L gas system components and capacities (CH4)

Phase 3 Stakeholder behavior analysis

**Input**
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPI in the L gas system and how would stakeholders respond to changing KPI? (CH6)

**Output**
1. Technical alternatives (CH6)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

Phase 4 Integrated scenario analysis and conclusions

**Input**
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond? (CH8,9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH8,9)
4. To what extent did the chosen modelling technique approach meet initial requirements? (CH10)

**Output**
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH9)
4. Recommendations to Dutch government and EDIN (CH11)
5. Reflection on modelling approach (CH10)

Figure 1.5 Outline of this research in 4 main phases and the research questions with their accompanying chapter numbers.
2 The L gas system

This chapter presents the results of the first phase of this research. This phase sets the definitions and the concepts of a natural gas system and in specific the North West European L gas system. After this phase, the reader will have sufficient knowledge about the L gas system to understand the line of reasoning in the other three phases. This chapter also identifies important characteristics of the L gas system that need to be addressed in the remaining of this research.

In the outline of this chapter one can see again the differentiation between the technical-physical part in chapter 2.1 and the socio-technical part in chapter 2.2. In chapter 2.1, the physical layer of the schematic overview in Figure 2.1 is presented and the relevant issues relating the components of this physical layer are discussed. Chapter 2.2 introduces the relevant stakeholders within the L gas system and discusses their general interests regarding gas quality.

Figure 2.1 The North West European L gas system in schematic form. Own composition, adapted from Correljé, de Vries et al (2010).

2.1 Physical layer of L gas system

The L gas system in North West Europe delivers L gas to the Netherlands and parts of Germany, France and Belgium. The proportions of this demand are shown in Figure 2.2.
In 2010, the system delivered a total of about 72 billion cubic meters (bcm). 50 bcm of this total demand was delivered by the large gas reserve in Groningen. About 12 bcm was produced in secondary sources of L gas in both the Netherlands and in Germany.

2.1.1 Upstream: L gas production

The discovery of the Groningen field has been the key driver for the development of the North West European L gas market, as this development was centralized around this gas field. Groningen is not only unique for its massive initial reserves, it is also unique because of its pattern of exploitation. The pressure in the field, the large number of wells and its linkage with UGS allow for a very flexible production of the field. The production of the field can easily be adjusted on a relatively short term. High production flexibility is a very valuable characteristic for a gas field.

Other sources than the Groningen field have only limited production flexibility. For smaller offshore fields, the production is maximized to recover the relatively large investments costs. Imported gas has a long travelling distance, which not only implies large investment costs but also makes it difficult to adapt the amount of gas to changing demand on the short term. Therefore, the Groningen field has an important function in providing for the demand fluctuations in the L gas system. Also, flexibility is provided by the associated Underground Storage facilities (UGS). An UGS is a depleted gas field or a salt cavern, in which gas can be injected in times of low demand (and low gas prices). This gas can be produced from these UGS in times of high demand (and higher gas prices).
2.1.2 Downstream: L gas consumers

The L gas system mainly provides gas for domestic end-users, while the H gas system delivers to 80 large industrial customers. Based on this customer base, L gas demand has a strongly fluctuating pattern. As domestic gas is mainly used for heating purposes, demand in summer months is much lower compared to the demand in winter months. This is called the seasonal fluctuation of demand. Also, gas demand fluctuates over the day, with peaks in the mornings and in the evenings. Finally, there is a weekly pattern of gas use, as a typical Monday has a different demand profile compared to a typical Sunday.

As the gas system has to provide for this fluctuating demand, a gas system does not only have to be physically able to deliver the commodity (the total yearly volume of gas demand) but also the production flexibility and production capacity to supply gas during peaks in demand (de Joode and Touber 2008).

2.1.3 Midstream: L gas trade

L gas is traded in two different ways: By Long Term contracts and on virtual trading hubs. The L gas that is traded on virtual hubs is mainly traded on TTF. Historically, Groningen gas was solely sold by Long Term contracts. These contracts contain a pricing formula, a minimum offset and a maximum offset. Because of the fluctuating demand patterns for L gas, these contracts allowed for a very flexible delivery (Melling 2010). These contracts were usually signed for a long period of contract time of 10-20 years, thereby adding to long term security of supply for end-users and long term security of demand for producers. The majority of L gas export contracts do not end before 2022, while most of these contracts have ended before 2030 (CREG 2010).

Over the last decade, sales on the TTF have gained ground (CERA and IHS 2011). The TTF, the Title Transfer Facility, is a virtual trading point on which buyers and sellers of natural gas can contract gas deliveries. Until 2009, H gas and L gas were traded separately on the TTF. In 2009 the quality label on TTF has been removed, with large consequences for the functioning of the L gas system as discussed later in this research.

This disappearance of the quality label has increased the liquidity of the TTF, as the two gas qualities are now considered to be one uniform product, thereby almost doubling the total traded volumes of this uniform product on TTF. Total volume of gas traded contributes to the liquidity of a market, and a high liquidity of the TTF is considered an important driver for a strong position of the Netherlands as a gas country and an important aspect of the Dutch gas roundabout strategy (EL&I 2009).

2.1.4 Midstream: Quality Conversion

The Dutch gas infrastructure was developed to transport two different qualities of gas past 1974. The smaller fields in the Netherlands are mainly H gasses and had a guaranteed off take under the small fields policy (de Vlam and Custer 2010). To provide for this guarantee in times of low H gas demand, Gasunie developed a system for blending all these different gas qualities to the L gas standards. After this treatment, the converted gas is also referred to as ‘pseudo-Groningen gas’. This conversion of H gas to L gas or to pseudo G-gas is done in two ways: by blending in blending stations and by adding nitrogen.
In blending stations H gas and L gas are blended into one uniform gas mixture. The proportion with which the different gas qualities are mixed defines the quality parameters of the output gas. The specifications set a range for the Wobbe index that the output gas has to meet. In total, 9 blending stations are installed in the Netherlands, with the most important ones in Ommen and Wieringermeer.

By adding nitrogen to H gas, the Wobbe index of this gas is reduced. In this way, it is brought within the specifications for the L network. Nitrogen is produced in air processing facilities and added to H gasses in blending stations. In the Netherlands, 5 nitrogen production facilities exist. As an indication, the blending proportion is circa one volume part nitrogen to six volume parts H gas. In Belgium, a country that imports large amounts of L gas from the Netherlands, the conversion costs are not socialized. There are some quality conversion facilities, of which buyers and sellers of gas can make use against regulated tariffs. In Germany, there are no conversion facilities present at the time.

In the past, shippers were responsible for balancing their gas sales on quality (for a more detailed description of this: see chapter 6.1). With the disappearance of the quality label on TTF in 2009, the responsibility for quality conversion shifted from the shippers and traders to GTS. This means that this role is now centralized at one place, thereby increasing the efficiency and the coordination of this task in the system. The costs for GTS to execute this task are socialized within the transport tariffs.

It appears that this introduction of socialization of conversion costs has led to a decrease in nitrogen use by optimalisation efforts of GTS. Reversed Quality Conversion (RQC), the virtual conversion of L gas to H gas by compensating for imbalances in the other direction, is used by GTS to maintain the balance between H gas and L gas without using nitrogen (Heren 2008).

Also other quality parameters than Wobbe index are defined in the infrastructure net codes. If a gas is not within these specs, the seller of this gas is not allowed to feed it in the national grid. Most gasses that are not within the specs have too high sulfur contents. Therefore, these gasses need to be processed before they can be fed into the grid. Gas Processing facilities in the Netherlands are among others located in Emmen and in Den Helder.

2.2 Stakeholders in the L gas system
Within the physical L gas system, of which the functioning has been described in chapter 2.1, multiple stakeholders are active in different parts of the system. In this chapter, the stakeholders are grouped into 7 main stakeholder groups. Per group, the specific stakeholders are introduced, and their general interests in the L gas system are described.

2.2.1 The “Gasgebouw”
When the Groningen field was discovered in 1959, the Dutch Government designed the so-called Gasgebouw to exploit this gas reserve. Gasunie was established in 1963 as a joint venture owned by the Dutch governments Mines (DSM) (40%), the Dutch government directly (10%) and ExxonMobil (25%) and Shell (25%). The latter
two private parties were united in the 50/50 joint venture NAM, the “Nederlandse Aardolie Maatschappij”.
Gasunie was responsible for buying, transporting and selling the natural gas. From 1963 on, Gasunie
coordinated the development of the gas pipeline infrastructure that connected all private households to the
national gas grid within 10 years. Also, the Maatschap Groningen was established for producing the natural gas
from the Groningen field. NAM, being the operator, had 60% of the shares and DSM the remaining 40%. Also,
DSM was instructed to hold a 40% state interest in all gas producing licenses and concessions to be granted by
the state. This structure is known as the “Gasgebouw” (Correlje, van der Linde et al. 2003; de Vlam and Custer
2010).

The liberalization of the European gas markets resulted in the split up of Gasunie in 2005. Its trading activities
were brought under GasTerra, with the same shareholders. Gasunie Transport and Services, later GTS, is
constituted as the independent system operator, the TSO. As national transmission system operator, GTS is
responsible for the management, the operation and the development of the national transmission grid on an
economic basis. The agreement between the State, EBN and DSM was modified to end DSM’s administrative
responsibility for EBN on January 1st in 2006. EBN continued as a state owned entity with its independent
Supervisory Board.

2.2.2 Stakeholders in the L gas system

**Upstream** in the system are the operators. In the L gas system, the most important operator is NAM as it
operates the Groningen field and most of the small L gas fields within the Netherlands. In Germany, the
operators are united in the WEG (Wirtschaftsvereinigung Erdöl- und Erdgasgewinnung e.V.). EBN is a main actor
in the upstream market in the Netherlands as it participates for 40% in gas fields within the Netherlands. Operators want to maximize the production of natural gas. For the upstream segment, it is important that they
can inject their gasses in the network without having to incur large costs to get the gas within the quality
specifications. Typically for the L gas system, the operators want to maintain the demand for the L gasses they
can produce. This can be done actively, both on the short term by increasing their sales as on the long term by
avoiding substitution of L gas.

**Midstream**, the main actors are the Transmission System Operators (TSOs) and the Distribution System
Operators (DSOs), as are the UGS operators. In the Netherlands, GTS is the sole TSO from which the state owns
100% of the shares. In Belgium, the TSO is Fluxys, a commercial company. In Germany, there are 5 TSOs active
within the L gas system: Gasunie Deutschland, GTG Nord, Nowega, Thyssengas and Open Grid Europe
(Netzentwicklungsplan 2012). The country specific differences between TSOs are of influence in the
considerations regarding investment decisions (Haase 2009). For a TSO, one main interest regarding gas quality
regards the match between entry specs and exit specs as this would limit the complexity of their function to
maintain the quality of gas in the system.

Within the North West European gas infrastructures, the system operators are responsible for the quality of the
gas in their networks. Within the Netherlands, GTS has to make sure that the quality of the gas in its
infrastructure is within the specifications set for that part of the infrastructure. These specifications are specified in so called netcodes and indicate the allowed range for the values of the different quality parameters for natural gas. For GTS, this means that it is responsible for quality conversion.

UGS operators in the L gas system are GTS, Nuon, RWE, NAM and EBN. UGS operators benefit from the price difference between low demand and high demand, as they buy gas in times of low prices and sell their gas in times of high prices. Therefore, a liquid and well-functioning TTF is in their interest as this supports their trading activities.

**Downstream**, the end-users of gas, are mainly households for the L gas system, represented by Distribution System Operators. For them, a constant gas quality is important for safety and for efficient burning processes. They value a low price for gas. Also, the costs to adjust to changing gas qualities needs to be minimal, as are the safety risks involved in this change.

**Traders and shippers** want unrestricted trading. They value a strong and liquid TTF and therefore the disappearance of the quality label at TTF was welcomed. In Germany and Belgium, there is still a separation of the two qualities which is experienced to be hindering the liquidity. In Germany, the conversion fee is gradually phased out. Examples of traders are DSOs like Essent and Nuon, and large scale users of L gas who contract their own gas like gas fired power plants.

GasTerra is the sole trader of Groningen gas. It buys and sells the Groningen gas. Induced by the interests of its shareholders, GasTerra wants to maximize the sales of Groningen gas. With the total gas sales limited to the production cap until 2020 the objective is to reach this maximum amount of Groningen gas that can legally be produced. After 2020, the objective of GasTerra is to produce at full capacity throughout the year.

**Manufacturers** of gas appliances have an interest in a small bandwidth and want to have certainty about the future specifications of gas so they can adjust their machines in time. In the Netherlands, a number of united bodies exist that represent the interests of manufacturers. In this research, an interview has been conducted at Zantingh BV, a producer of medium to large gas burning appliances.

For the Dutch government, a cheap, safe and reliable gas supply for its residents is important. Also, it wants to optimize its profits from the exploitation of natural resources. For the L gas system, the Dutch government wants to secure the value of the Groningen field as it accounts for a significant part of the total state budget. In the past, measures were taken to maintain the Groningen gas as a strategic reserve. The production cap on Groningen production is a heritage of this policy.

De Joode and Touber (2008) have identified 4 main roles of the Dutch government in a liberalized gas market:
• It influences the functioning of the system by means of the Natural gas law and “Ministeriële Regelingen” (“secretarial arrangements”), in which both the security of supply for small consumers and the optimal extraction of small fields have been secured.

• It is supervisor of competition within the gas market (through NMa) and the use and management of the transmission and distribution networks (through the “Energiekamer” (Energy chamber) of NMa).

• Is the owner of the national transmission network (through Gasunie)

• Is shareholder in the national trading company GasTerra (10% directly and 40% via EBN)

Finally, competition authorities also consider market liberalization as an important value in European politics. Free movement of goods and a competitive market are pursued to increase efficiency and to create a level playing field. Especially infrastructures, being natural monopolies, are strictly monitored to enable competition. L gas has attracted attention with GasTerra being the main supplier of L gas. In the Netherlands, NMa is the regulatory body but it mainly has an executive role. In Belgium, the CREG takes up a leadership role in the discussion about the future of the L gas system. Also in Germany, BNetzA is more active in the L gas market compared to the NMa. Possible reasons for these different roles are the level of state ownership of the TSOs and the history in the Netherlands with “het Gasgebouw”. This is discussed more extensively in Chapter 6.

2.3 Conclusions phase 1

With this grouping of the relevant stakeholders the first phase is finished. After this phase, the reader is familiar with the basic concepts of the L gas system. The concepts and the definitions are set and the main characteristics of the L gas system are described. In the next phase this knowledge is used to choose the right modeling methodology in order to meet the model requirements as set in the problem statement.
### Phase 1 Background: General functioning L gas system

#### Input
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH2)

#### Output
1. Concepts and definitions natural gas systems (CH2)
2. Basic understanding L gas system (CH2)
3. Main stakeholders and interests regarding gas quality (CH2)
Phase 1 Background: General functioning L gas system

Input
1. What are the main characteristics of the L gas system and how is it operated? (CH12)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH12)

Output
1. Concepts and definitions natural gas systems (CH12)
2. Basic understanding L gas system (CH12)
3. Main stakeholders and interests regarding gas quality (CH12)

Phase 2 Modeling

Input
1. What are the requirements and objectives for the modeling approach? (CH13)
2. What modeling technique can be used to reach these objectives? (CH13)
3. How is this general modeling technique applied to the NWE L gas system? (CH4.5)

Output
1. General modeling approach (CH13)
2. Method of supply sources (CH13)
3. Main system constraints (CH3.4)
4. L gas system components and capacities (CH4)

Phase 3 Stakeholder behavior analysis

Input
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPI in the L gas system and how would stakeholders respond to changing KPI? (CH6)

Output
1. Technical alternatives (CH16)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

Phase 4 Integrated scenario analysis and conclusions

Input
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond? (CH8.9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH8.9)
4. To what extent did the chosen modeling technique approach meet initial requirements? (CH110)

Output
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH4.9)
4. Recommendations to Dutch government and EBN (CH111)
5. Reflection on modeling approach (CH110)
3 Modeling the physical flows within a gas system

After the first research phase ended and concluded with a general understanding of the functioning of the L gas system and its main stakeholders, this second research phase clarifies on the technical-physical complexity of the L gas system. This complexity expresses itself in uncertainty about the impact of the decline in L gas production capacity to the physical flows within the system and its functioning. This phase aims to answer the following research questions:

1. What are the requirements and objectives for the modeling approach?
2. What modeling technique can be used to reach these objectives?
3. How is this general modeling technique applied to the NWE L gas system?

In chapter 3.1, the modeling objectives are set, resulting in the choice for Linear Programming as a method to reach these objectives. Chapter 3.2 briefly introduces the general concepts of Linear Programming and its use to natural gas networks. In chapter 3.3 the main modeling assumptions are worked out. This chapter is split up in the two main factors of the modeling approach: the merit order of supply sources and the system constraints. Chapter 3.4 introduces the model set-up, setting the time span for the simulation and other modeling parameters.

3.1 Modeling objectives and approach

It is clear that the decline in production capacity of the large gas reserve in Groningen will affect the total supply of L gas. But there are different views about whether this would influence the ability of the system to provide for the demand, and about the necessity and effects of the different investment options. In this chapter a modeling approach is introduced that quantitatively addresses these questions. The objective of this modeling step was to answer the following questions:

1. What is the effect of declining production capacities to the technical ability of the system to provide for the demand for L gas? Will an imbalance between demand and supply appear, and if so, on what term?
2. How will different investment options of stakeholders influence the physical flows within the L gas system?
3. How will changing parameters within the system affect the utilization of the Groningen field, storage facilities and conversion facilities?
As explained earlier, many stakeholders are interested in a more detailed simulation tool that extends the analytical capabilities of existing models. However, it appeared to be difficult to capture these interactions and complexities within the system in a workable and accessible model. This thesis presents a model that combines these requirements. The objective was to create a model that is:

- Accessible; easy to understand for external parties
- Workable; easy to adapt to changing parameters
- Quick; short running time to quickly scan effects of changing parameters
- Representative; creating a representative understanding of the L gas system to its users

Based on these modeling questions and modeling requirements, this chapter elaborates on the choice for Linear Programming and the set-up of a LP problem for a general gas infrastructure.

3.1.1 Choice for Linear Optimization

A typical gas system is designed to match the supply and the demand at any given time. In order to do so, different types of system components exist. The ability of a gas system to provide for the demand is limited by the technical limitations of these system components.

The North West European L gas system is a confined system, with only a limited number of supply sources and demand that is dedicated to the specific gas quality provided by these sources. It is loosely coupled to the European H gas system by blending and conversion facilities, in which quality specifications and conversion capacity limit the supply from other sources but the L gas production. This regional, dedicated demand supplied by a limited number of supply sources is a crucial characteristic of the system in that it allows the flows within the L gas system to be simulated in a comprehensive and detailed way.

Within the system, different supply sources exist to provide for the demand for L gas. These supply sources do not only differ in volume and production capacity, but also in production costs and contractually established production schemes. Theoretically, in a competitive market the utilization of the cheapest source will be maximized before the second cheapest source will be used. In the Dutch L gas system, some gasses with higher production costs are to be produced first, as a consequence of the Dutch small fields’ policy. Assuming this, a merit order of supply sources can be specified that reflects the order in which the different sources for L gas are utilized.

Concluding the preceding, the L gas system is operated as a network that satisfies demand with minimal total costs of the system, under the technical limitations put down on the system by both the different components and the way these components interact. This is a typical problem that can be solved by a network optimization. In this case, those relations are mostly linear, or can be expressed in linear form. Therefore, in this research a model
is built that uses Linear Optimization as a mathematical method to simulate the flows within the L gas system in North West Europe.

3.2 Linear Programming

3.2.1 General LP problem

In Linear Programming, a linear objective function is optimized (maximized or minimized) over a convex polyhedron specified by linear and non-negativity constraints (Midthun 2007). The founder of linear programming (LP) is considered to be George B. Dantzig in 1949; in 1991 Dantzig presented an overview of the development of LP (Dantzig 1991). Midthun (2007) gives the following example of a general LP problem:

\[
\begin{align*}
\text{Max} & \quad c^T x \\
\text{Subject to} & \quad Ax \leq b \\
& \quad x \geq 0
\end{align*}
\]

The first function represents the objective function that has to be optimized while fulfilling the constraints that are given below this objective function. In figure 3.1 a graphical representation of a simple LP problem is given. The arced area is the 'feasible area', the area that lies within the constraints. In this example, the area is constrained by the constraints:

\[
\begin{align*}
x \geq 0 \\
y \geq 0 \\
x \geq y \\
x \leq 20
\end{align*}
\]

As the objective function is always linear, the optimal solution will always be on the boundary of the feasible area, and either at one corner point or at the line between two corner points. Therefore, solving a LP problem can be done by systematically calculating the values at the objective function at corner points. There are different ways of doing this efficiently so that you don’t have to calculate for every corner point.

3.2.2 Linear Programming of natural gas networks

Using Linear Programming for natural gas network optimization has been used extensively in scientific literature. Zheng, Rebennack et al (2010) have presented a detailed discussion on the use of optimization models on three different key applications: the natural gas production, the natural gas transportation and the natural gas market. Within the Netherlands, the study "Math in Gas and the art of linearization" (van der Hoeven 2004) gives
a very detailed description of how the many non-linear relations within a natural gas network can be linearized to make them applicable.

In modeling a natural gas network by optimization methods, the tradeoff between level of accurateness and accessibility of the model is well understood. Midthun (2007) describes this tradeoff “between accurately describing the properties of the transportation network, and being able to solve the model”. The studies introduced above pursued to model the exact capacities and pressures within natural gas pipelines as precise as possible in order to operate these pipelines. This research focuses on the long term ability of the L gas system to match supply and demand. Therefore, different requirements to the LP model for this study exist.

Butler and Dyer (1999) have identified timing issues in their modeling study in which they wanted to give operational planning advice on both short term and long term, being 1 year. They had to aggregate their daily time step in order to maintain the short modeling time and therewith the workability of their model. Although criticized by Midthun (2007), Cremer, Gasmi and Laffont (2003) have assumed one static capacity per pipeline. This would not take into account the difference between minimal pipeline pressure and maximum pipeline pressure, for example, but it does simplify the model and therewith the workability of the model.

This search for the right level of complexity in the model is best described by Mulder and Zwart (2005): “A model of the gas market is a description of the real market, capturing its fundamental features. To construct an empirically well founded model, it is necessary to consider the essential characteristics of the European gas market.” In order to achieve the specific requirements to the model in this research it is key to find these essential characteristics for the European L gas system.

3.3 Main modeling assumptions

In the preceding chapters, the modeling approach is defined as: “Optimization of utilization of supply sources according to a merit order, to supply demand within the technical constraints of the system”. This description covers the two main components in this modeling approach: The system constraints and the merit order of supply sources. In this chapter, the choice for these physical constraints in the system and the merit order of sources is discussed, as are the underlying modeling assumptions.

3.3.1 5 Types of constraints

In this chapter, 5 types of constraints in a natural gas system are presented. The choice for the constraints is validated and a general mathematical description for every type of constraints is given. The 5 constraints are:

1. Demand constraints
2. Production constraints
3. Storage constraints
4. Quality Constraints
5. The existence of physical connections

Firstly, it is assumed that the system has to fulfill the demand for L gas at any given time. As L gas is mainly supplied to households, that use it to cook and to heat their water and their houses, and to small commercial consumers, people are dependent in their daily lives on this supply. Disruptions in supply are not accepted. Therefore, demand is considered to be a constraint in the model. In mathematical terms, with \( P_i \) being the production of production node \( i \) at time \( t \) and \( D_t \) being the demand at time \( t \), this type of constraints is of the form:

\[
P_1 + P_2 + P_3 = D_t
\]

A second type of constraints in the model is production constraints. Production of natural gas is limited by the technical withdrawal capacity of these fields, and the remaining reserves within the field. Typically, the withdrawal capacity will decrease over time when the reserve gradually gets depleted. Generally, with \( P_1 \) being the production of supply source 1 at time \( t \), and \( C_1 \) being the maximum production capacity of this source at time \( t \), a production constraint is of the form:

\[
P_1 \leq C_1
\]

\[
P_1 \geq 0
\]

Also, nitrogen production for quality conversion and injection and withdrawal rates for Underground Gas Storages are of this type. Nitrogen production is constrained by the available production capacities of installed facilities. Storage injection and withdrawal capacities are not only constrained by technical limitations, but also by the pressure within the storage. Injection capacity is at its maximum when the pressure in the field is low, e.g. when the storage level is relatively low. Withdrawal capacity is at its maximum when the pressure in the field is high, e.g. when the storage level is high. This relation is reflected in Figure 3.2.

![Examples of injection and withdrawal curves: aquifer](image)
In this type of constraints, the maximum production rate at time t is dependent on the actual amount of gas present in the storage at this time. However, it is not possible to linearize a relation in which two non constant values are interrelated to each other. In this simulation, this non-linear relation is expressed in a linear way by using the storage level of one time step earlier than the actual time of simulation. In this way, the non-linearity of this relation has been changed into a linear one. With $r_{t-1}$ being the factor to translate the stock level as a percentage into the injection rate as a percentage, $I_t$ being the injection rate at time t, $I_{\text{max}}$ being the maximum injection rate at time t and $S_{t-1}$ being the stock level at time t-1, this type of constraints are of the form:

$$\frac{I_t}{I_{\text{max}}} = \left( \frac{S_{t-1}}{S_{\text{limit}}} \right) \cdot r_{t-1}$$

A third type of constraints is **storage constraints**. Underground gas storages (UGS) are used to provide for both the seasonal and the daily fluctuations in gas demand by storing gas in times of low demand or low price levels, and delivering gas in times of peak demand or peak price. An UGS system is constrained by its injection capacity, its storage capacity (= Working Volume) and its withdrawal capacity. Again, injection and withdrawal capacity are dependent on the pressure within the Storage. This type of constraint is mathematically represented in the following set of equations:

$$S_t = S_{t-1} + I_t - W_t$$

$$S_t \leq WV_{\text{max}}$$

$$S_t \geq 0$$

$$S_0 = WV_{\text{max}=0}$$

With $S_t$ being the Storage level at time t, WV being the maximum Working Volume at time t, I and W being the Injection and Withdrawal rates for this particular UGS system. With the final equation, the initial level of the Storage is set at the maximum Working Volume at t = 0, implying that the storage is at its maximum level at the beginning of the simulation.

Similar to this type of constraints is the situation in which a product or a process needs to be balanced in every time step, with no storage capacity. In this research it is assumed that time delays within pipelines are negligible.

A blending station in which 2 incoming production flows P1 and P2 are blended and distributed to one demand region and one storage injection process is constrained by:

$$\text{In} = \text{Out} = P_{1t} + P_{2t} = D_t + I_t$$

The fourth type of constraints used in this model is **quality constraints**. The TSO is legally responsible to maintain the quality within the boundaries as specified in the netcodes. The main parameter in this system is the
Wobbe-index. The Wobbe-index is a measure of the combustion velocity of the gas, which is calculated by the heating value of the gas divided by the square root of the relative density. In blending stations, gases with a varying Wobbe are to be blended within the Wobbe range as set in the quality specifications. This Wobbe range sets a minimum value and a minimal value for the Wobbe after this blending station. For modeling reasons, the varying Wobbe are to be blended within the Wobbe range as set in the quality specifications. This Wobbe range is assumed to be linear, e.g. the Wobbe of two flows with equal volume is the average of their two Wobbe values. Based on this assumption, this type of constraints can be expressed as:

\[
\frac{P_1}{P_1 + P_2} Q_{P_1,t} + \frac{P_2}{P_1 + P_2} Q_{P_2,t} \leq Q_{\text{max},t}
\]

\[
\frac{P_1}{P_1 + P_2} Q_{P_1,t} + \frac{P_2}{P_1 + P_2} Q_{P_2,t} \geq Q_{\text{min},t}
\]

With \( P_1 \) and \( P_2 \) being to production sources before the blending station, \( Q_{P_{1,2},t} \) being the quality of this flow at time \( t \), and \( Q_{\text{max},t} \) being the maximum Wobbe value at that blending station at time \( t \).

This constraint may appear to be non-linear; however, after changing the inequality sign in an equality sign, the formula can be rewritten as:

\[
P_1 Q_{P_1,t} + P_2 Q_{P_2,t} = Q_{\text{max},t} \left( \frac{P_1}{P_1 + P_2} \right) \]

\[
(P_1 (Q_{P_1,t} - Q_{\text{max},t}) + P_2 (Q_{P_2,t} - Q_{\text{max},t})) = 0
\]

As \( (Q_{P_{1,2},t} - Q_{\text{max},t}) \) is a constant, this equation is a linear combination of \( P_1 \) and \( P_2 \).

The final and most obvious type of constraints in the system is the existence of physical connections. The distribution of gas is constrained by the existence of pipelines from put to pit. As the L gas system is typically unidirectional, roughly from North to South, the existence of a connection between to nodes is essential to allow for this flow. This type of constraints is modeled as any equation within the set of constraints. If a relation between two network points is not expressed in any of the constraints, a flow between these two network points is not possible.

This type of constraints is used to combine the other constraints discussed in this chapter. It forms the cement of the simulation as it connects all gas system components to each other. As an example, the situation in which two production sources can solely be used to fill one Underground Storage is described in the following equation:

\[
P_1 + P_2 = l_t
\]

Generally, with \( n \) the total number of production nodes, the existence of a physical connection with an injection node can be described by:
\[ I_t = \sum_{i=1}^{n} \psi_i P_i \]

With

\[ \psi_i = \begin{cases} 1, & \text{when } P_i \text{ is coupled to } I \\ 0, & \text{when } P_i \text{ is not coupled} \end{cases} \]

3.3.2 Other constraints outside the scope

Next to the five types of constraints used in the LP problem there are some constraints that might impact the functioning of the L gas system, but that are not taken into account in this simulation. These constraints are explained in this chapter, as are the underlying assumptions for this modeling choice.

Transport of gas is constrained by pipeline capacity. A transportation pipeline has a certain capacity that limits the amount of gas it can transport. In a LP problem, this capacity can be modeled as a new type of constraints. However, this would increase the number of nodes and thus the complexity and accessibility of the model. If every pipeline and its capacity would be included in the simulation, the number of nodes would explode. Based on the following assumptions, leaving these constraints out of the model does not affect the applicability of the model.

1. Objective is to balance demand and supply. Both are estimated to decline, providing for the assumption that current capacity is sufficient in the future.

2. It is assumed that a secure gas supply is prevailed above minor investments in pipeline capacity.

As described in the requirements, the main objective of the model is to monitor the balance between demand and supply. At this time, transport capacity is sufficient to supply current demand. Issues might arise because of a decline in supply, a significant increase in demand is not assumed to occur. From this, it can be concluded that current capacity is roughly sufficient to meet demand in the future. Secondly, considering the importance of a reliable supply of gas, it is assumed that pipeline capacity is maintained at a sufficient level to secure this supply.

However, this does not mean that pipeline capacity is not taken into account in this simulation. Firstly, in the L gas system some capacity constraints are important for the functioning of the system. These capacities include the pipeline from Groningen to the province of North-Holland and the border capacities. This will be further elaborated on in chapter 5. Also, in discussing the results of the simulation, indicators of capacity problems will be used to assess the feasibility of policy responses.

Secondly, while designing possible scenarios and the behavior of stakeholders within these scenarios, capacity bottlenecks will be taken into account. Existing capacity is an important criterion in creating feasible scenarios. However, the amount of bottlenecks is limited and do not justify the disadvantages of implementing this constraint for this research. Therefore, capacity constrains the range for certain input data and not as a general
constraint in the model. A good example is the export capacity to Belgium, which is limited by the capacity at border point in Hilvarenbeek. Therefore, a growth scenario for Belgium L gas demand is not considered feasible (see chapter 8).

A second constraint that is not considered is the availability of H gas at blending stations that might be limited. Security of supply of gas is an important value in the Netherlands and therefore it is assumed in this research that a lack of L gas has to be compensated for by other sources. As H gas is the only substitute, as there is an abundance of H gas supply worldwide and as the H gas system lies outside the scope of this research, it is assumed that the supply of H gas is not a limiting factor in this simulation. The demand patterns of H gas in the simulation outcomes should be assessed critically, however, in order to evaluate the feasibility of such a demand pattern.

3.3.3 A merit order of sources

The modeling approach is defined as: *Optimization of utilization of supply sources according to a merit order, to supply demand within the technical constraints of the system*. Next to constraints, the second main component of this approach is the merit order of sources. This merit order forms the objective function of the LP problem. The merit order is of the type:

\[
\text{MINIMIZE} \quad \alpha_2 P_{1s} + \beta_2 P_{2s} + \gamma_3 P_{3s} + \delta_4 P_{4s} + \varepsilon_5 P_{5s}
\]

With \( \alpha, \beta, \gamma, \delta, \varepsilon \) etc. being the costs per unit of production at time \( t \) for the production process behind \( P_1 \), and \( P_1 \) the total amount of units produced at time \( t \) in the process behind \( P_1 \). For the costs \( \alpha, \beta, \gamma, \delta, \varepsilon \) virtual costs have been assigned in this research. These virtual costs reflect the order in which the production capacity of these sources is used, while maintaining within the constraints of the system. By minimizing these virtual costs, this order is followed when solving the LP problem.

As there are different supply sources within the North West European L gas system, not all supply sources will produce at full capacity. In a fully competitive market, a supply source would produce gas if its marginal producing costs would be lower than the market price. In the North West European L gas system, this theory does not entirely work due to historic reasons and the specific characteristics of the Groningen gas field. In this model, a merit order of supply sources is assumed. This means that all supply sources are prioritized and that a supply source is not used before production from sources further up in the merit order is constrained by either production capacity or one of the other constraints. Specifically for the L gas system, this research has designed this merit order as:

1. L gas production of small fields (sometimes off spec H gas) and German production
2. L gas production in Groningen
3. L gas in UGS
4. H gas blending (until upper Wobbe range)

5. H gas + nitrogen

In the Netherlands the small fields policy ensured small gas fields that GTS would accept at least 8000 hours of utilization over the year. In the Netherlands, there are three points at which L gas production from small fields is injected within the system. As these amounts are relatively small, this production is never limited by demand and therefore there is no need to assume an order between these sources. The same counts for the L gas production in Germany. Based on this small fields policy, it is assumed that this source of supply is on top of the merit order.

Secondly, the large Groningen field is used to fulfill demand. Its marginal production costs are low because of the large initial reserve and the natural pressure within this gas field. Therefore it is attractive to produce this gas at any price (Mulder and Zwart 2006). Production of this field is not only used to provide for current demand but also to fill Underground Gas Storages. As stated, the total production in Groningen is limited by a yearly production cap set by the Dutch government.

Thirdly, it is assumed that L gas storages are used. The reason for this assumption is that L gas storages are usually filled with the (cheap) Groningen gas and that this gas is always cheaper than the other sources of gas, even including the storage costs. However, in the storage injection season, typically from April 1st until October 1st, it is assumed that storages are not used for supply and therefore its production capacity is assumed to be zero.

Generally, storages can be categorized as salt caverns, aquifers and depleted gas fields (GSE 2010). Salt caverns and aquifers typically have a small working volume and a relatively large withdrawal capacity. These storages are mainly used for within day fluctuations. Depleted gas fields typically have a larger working volume and are therefore more suitable to cover for the seasonal fluctuations in demand.

This difference between the two types of gas storages is reflected in the model in lower costs per unit for a depleted gas field, against small start-up costs for this field. In doing so, an aquifer would be preferred for short peaks, while a depleted gas field would be preferred when a storage facility is expected to produce over a longer period of time.

Fourthly, H gas is blended into the L gas system to increase the total volume of L gas when the typical L gas production sources do not satisfy demand. Generally, H gas has higher marginal production costs compared to Groningen gas and therefore it is a valid assumption that H gas will only be used when the capacity from other sources is not sufficient. This injection is limited by Wobbe range of L gas, as injecting H gas will increase the Wobbe in the entire system. Based on the earlier assumption of unconstrained H gas supply, the simulation tool does not differentiate between H gas from storages and H gas from gas fields.
Finally, when all other supply sources are not sufficient to satisfy demand, H gas is diluted with nitrogen to bring this gas within the quality specifications of the L gas grid. As nitrogen production is expensive, these supply sources are assumed to be the last sources that are put into operation in the L gas system.

### 3.3.4 A general LP problem for a gas infrastructure

Based on the preceding chapters, this chapter presents a general LP problem for a gas infrastructure. The constraints are general formulas for this type of constraints and therefore this problem does not form a LP problem on itself that can be solved.

**Objective:** MINIMIZE

\[ \min \{ \lambda P_{1e} + \beta P_{2e} + \gamma P_{3e} + \delta P_{4e} + \varepsilon P_{5e} \} \]

**Subject to:**

#### Demand constraints

\[ P_{1e} + P_{2e} + P_{3e} = D_e \]

#### Production constraints

\[ P_{1e} \leq C_{1e} \]

\[ P_{1e} \geq 0 \]

#### Storage constraints

\[ \frac{I_e}{I_{e_{\text{max}}}} \leq \left( \frac{S_{e-1}}{S_{e_{\text{max}}}} \right)^{\epsilon} I_{e_{\text{max}}} \]

\[ S_e = S_{e-1} + I_e - W_e \]

\[ S_e \leq W_e V_{e_{\text{max}}} \]

\[ S_e \geq 0 \]

#### Quality constraints

\[ \frac{P_{1e}}{P_{1e} + P_{2e}} Q_{P_{1e}} + \frac{P_{2e}}{P_{1e} + P_{2e}} Q_{P_{2e}} \leq Q_{\text{max}} \]

\[ \frac{P_{1e}}{P_{1e} + P_{2e}} Q_{P_{1e}} + \frac{P_{2e}}{P_{1e} + P_{2e}} Q_{P_{2e}} \geq Q_{\text{min}} \]

#### Physical constraints

\[ I_e = \sum_{t=1}^{10} \varphi_t P_{1e} \]

**With**

\[ \varphi_t = \begin{cases} 1, & \text{when } P_t \text{ is coupled to } I \\ 0, & \text{when } P_t \text{ is not coupled} \end{cases} \]
3.4 Model set-up

3.4.1 Time parameters

Within the Netherlands policymakers explore the possibility to maintain demand under current quality specifications until 2030. When assessing the functioning of the L gas system, the model should be able to evaluate the feasibility of this policy and its consequences. Therefore, a time span of 20 years is used in this model. As the system has to provide both commodities as production capacity, a time step of one day is used. This covers for both the total supply of L gas during the year as well as peaks in demand in cold winter days.

In Linear Optimization, constraints can reflect not only limitations for the current time step but also for time steps in the future. An example of this is the injection of storages. By recognizing the future demand for production capacity from storages set in those future constraints, the storages will get injected in times of low demand. For the number of optimization steps, 183 days is used in this simulation. This implies that all constraints and objective functions within the LP problem are not only set for time $t$, but for time $t$, $t+1$, ..., $t+182$. As an example, the objective function and the general formula for a demand constraint is extended to a 183 days' time span:

MIN

\[
\alpha P_{1c} + \beta P_{2c} + \gamma P_{3c} + D_{c} \geq \sum_{t=0}^{182} \alpha P_{1c+t} + \beta P_{2c+t} + \gamma P_{3c+t} + D_{c+t}.
\]

Subject to

\[
P_{1c} + P_{2c} + P_{3c} = D_{c}
\]

\[
P_{1c+1} + P_{2c+1} + P_{3c+1} = D_{c+1}
\]

\[
\vdots
\]

\[
P_{1c+182} + P_{2c+182} + P_{3c+182} = D_{c+182}
\]

As can be seen, increasing the look-ahead time drastically increases the number of constraints and therefore the solving speed. In using Linear Programming for a general gas infrastructure, this aspect has to be taken into account when determining the model parameters.

The reasoning behind the choice of 183 days is as follows. As the filling curve of a storage facility usually has a period of one year (from 0% to 100% to 0% in one year), the simulation would ideally optimize over the next 365 days. However, using 365 had slowed down the solving process too much (see validation, chapter 5). Instead, the assumption is made that the lower bound of storages at the beginning of the winter (1 October) is the maximum working volume of that storage. This means that all gas storages will be filled to a maximum in the beginning of the winter. Now, the optimization steps can be reduced to half a year, 183 days.
The simulation is set to simulate over gas years. A gas year starts at 1 October in a given year. In this model, the first time step corresponds to 1 October 2011. Typically, a gas day starts at 6:00 am and ends at 5:59 am the next day. The simulation ends on 1 April 2031. This is the last day of the winter. As the modeling objectives are to find the limits to the system and the limits to the system are required during times of high demand in winter time, the summer of 2031 is not simulated anymore. This means that the total modeling time is 7118 days.

3.4.2 Scale Units
In describing natural gas flows, different scale units are used. It can either be expressed in volume, cubic meters, or in energy content, Joule. As not every cubic meter of gas has the same energy content, in this research a cubic meter of gas refers to a cubic meter in Groningen equivalent, being gas with an energy content of 35,17 MJ/m$^3$, if not stated differently.

The main purpose of a gas system is to transport gas from put to pit. The demand for gas is a demand for energy. As the energy content of one cubic meter can differ within the system given the Wobbe-index of the gas supplied, the default scale unit used in this model is GWh. This choice is made because it is not possible in a LP problem to adjust the quality of a flow at time $t$ based on the composition of that flow in time $t$, as this is not a linear relation. Therefore demand in cubic meter does not allow for the changing qualities of the gas delivered.

This modeling choice has consequences for other nodes in the system. As production and storage capacities are typically expressed in cubic meters, it is assumed that the average energy content of each of these gasses is constant throughout the modeling time. Based on this assumption, the factor to calculate the energy content in GWh from a certain volumetric unit is considered constant. This allows for solving with Linear Programming.

For production, this is a valid assumption. However, for some storages, the gas quality can change over time and therewith the energy content of these flows. It assumed that these inaccuracies are small compared to the situation in which demand would be taken in cubic meters. This assumption is valid, as storages are generally filled in a period of 6 months, making the quality of these storages relatively insensitive to short term quality fluctuations.

For nitrogen production, this modeling choice has implications as well, because nitrogen has zero energy content. For modeling purposes, nitrogen has been assigned with an energy content of 0,01 MJ/m$^3$. This makes it possible to model nitrogen production capacity.
Phase 1 Background: General functioning L gas system

Input
1. What are the main characteristics of the L gas system and how is it operated? (CH12)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH15)

Output
1. Concepts and definitions natural gas systems (CH12)
2. Basic understanding L gas system (CH12)
3. Main stakeholders and interests regarding gas quality (CH12)

Phase 2 Modeling

Technical-physical complexity

Input
1. What are the requirements and objectives for the modeling approach? (CH13)
2. What modeling technique can be used to reach these objectives? (CH13)
3. How is this general modeling technique applied to the NWE L gas system? (CH4-5)

Output
1. General modeling approach (CH4)
2. Model order of supply sources (CH4)
3. Main system constraints (CH3.4)
4. L gas system components and capacities (CH4)

Phase 3 Stakeholder behavior analysis

Socio-political complexity

Input
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPI in the L gas system and how would stakeholders respond to changing KPI? (CH6)

Output
1. Technical alternatives (CH6)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

Phase 4 Integrated scenario analysis and conclusions

Input
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond? (CH8-9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH8-9)
4. To what extent did the chosen modeling technique meet initial requirements? (CH10)

Output
1. B policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH9)
4. Recommendations to Dutch government and EBIIN (CH10)
5. Reflection on modeling approach (CH10)
4 Using LP to model the NWE L gas system

In the preceding chapter, LP has been proposed to make a workable and accessible model of a natural gas system in general and the North West European L gas system in particular. The choice has been made for 5 key constraints and a merit order of sources is designed that rank the order in which the different production nodes within the system are being used.

Now we have set the general LP problem for a natural gas system, this chapter will fill in this LP problem for the NWE L gas system in particular. In chapter 4.1, an overview is given of all system components and their relations to each other. In chapter 4.2, the specific data to each of these components is presented. Together, this is combined in the design of the simulation tool in chapter 5.

4.1 System components in the L gas system

The North West European L gas system provides low calorific gas to the Netherlands, and parts of Belgium, France and Germany. The entire system is bounded to this region. In this chapter the different components and their capacities are specified. A simplified overview of the North West European L gas system is presented in figure 4.1. This overview is mainly based on information at the online data port of GTS and on information in the yearly published GTS TSC (“transport condities”).

Central in this diagram are the blending facilities, which have the function of bringing the various flows that enter these facilities within the quality specifications at the demand nodes. A central role at those blending stations is assigned to GTS, the TSO in the Netherlands. GTS is responsible for maintaining the quality of the gas and for facilitating the demand. The main blending facilities are in Ommen, Wieringermeer and Beekse Bergen. In Germany, two main blending stations are in use: Grossenkneten and Vogtei. In France and Belgium there are no large blending facilities. Quality constraints in the model are implemented at blending stations as these are the points at which different gas qualities are blended.

Within the system, the gas quality can theoretically vary from a minimum Wobbe of 43,4 MJ/m³ in parts of the Netherlands to a maximum Wobbe of 46,5 MJ/m³ in Germany, Belgium and France. These quality specifications are set in so called ‘netcodes’. It is the task of the Transmission System Operator to maintain the Wobbe–index of the gasses within the range as specified in the netcodes. For the distribution in the Netherlands, the allowed Wobbe range is between 43,46 – 44,41 MJ/m³. For export stations, two Wobbe ranges exist: At some stations, the export gasses are within the Dutch Wobbe range, other export stations have a Wobbe range of 45 – 46,5 MJ/m³.
Different production sources are included in the system. The main production source is the Groningen field. Smaller production fields enter the system via Emmen GZI (“Gas Zuiverings Installatie”) and are transported to blending facility in Ommen. In Kootstertille, H gas with a calorific value too low for the H cal grid, called “off spec H gas”, is diluted with locally produced nitrogen and injected in the L gas system. Small offshore gas fields that produce L gas come onshore in the LoCal pipeline and are blended in the L gas system at Wieringermeer. In Germany, two production areas are located: Weser/Ems and Elbe/Weser. Production from these fields is blended in respectively Grossenkneten and Vogtei.

Nitrogen production facilities are mostly located close to the main blending stations to allow blending in those stations. The main production is in IJmuiden, connected to Wieringermeer, and in Ommen. Per September 2012 a nitrogen production facility has become operational in Heiligerlee, in the North East of the Netherlands. With a
relatively low production capacity, a nitrogen storage facility is installed to provide for a high peak capacity. In Belgium, nitrogen is produced in Lilo and in Loenhout. In Germany and France, no nitrogen production facilities are installed.

As the main supply source is the Groningen field, the German, Belgian and French demand is mostly provided through export points from the Netherlands. For German demand, the most important ones are in Oude Statenzijl, Winterswijk and Zevenaar. Oude Statenzijl exports gas within the Dutch specifications; Winterswijk and Zevenaar export gas within the higher Wobbe range of 45 – 46.5 MJ/m³. The same counts for the main export point to Belgium in Hilvarenbeek. French demand is supplied through the Belgium/France border point in Blaregnies.

Smaller export points are in Dinxperlo, Haanrade and Tegelen (from the Netherlands to Germany) and in Zandvliet (from the Netherlands to Belgium). The flows over these border points are not published by GTS because the flows are too small and therefore commercially sensitive to publish. In this modeling study, these flows are not taken into account as different interviews within the industry have confirmed the assumption that these flows are negligible in size.

Within the system, Underground Storage Facilities provide for the seasonal and daily fluctuations in demand. The main storage facilities for L gas are in the Netherlands in Norg, Zuidwending and Alkmaar, in Germany in Epe and Nüttermoor and in France in Gournay sur Aronde. Belgium does not have any UGS. For modeling purposes, it assumed that the quality of gas in the storage is of a constant quality. This quality is assumed to be the average quality in its quality area as described in GTS public document “Beschrijving Gaskwaliteitssysteem, zomer 2011” (GTS 2011). As the storages are filled over a longer period time, taking this average value is a valid assumption (see 3.4).

The system ultimately delivers L gas to demand points. Only in the Netherlands, about 1500 GOS, Gas receiving stations, exist. These are aggregated in 4 main areas, according to the division GTS made in the earlier mentioned “Beschrijving Gaskwaliteitssysteem zomer 2011”. According to this document, 4 quality areas can be identified within the Dutch L gas system. Every GOS within this area receives gas with the same quality. To fulfill to the requirements of the model as set in chapter 3.1, this level of aggregation level is sufficient. For Germany, Belgium and France, L gas demand is aggregated at a national level. With the limited number of supply sources in these countries, a more detailed aggregation level would not lead to different model outcomes.

4.2 Data Specification

This chapter presents all the data and capacities of the different components within the L gas system. In this chapter, the graphical representation of this data is presented so that a general trend can be identified. Although because of modeling reasons the metric unit used in the simulation tool is in energy content (GWh), this chapter provides the data and capacities in volumetric parts because this is a more intuitive unit for readers.
4.2.1 L gas production

L gas production is limited to 6 sources: Groningen production, German production in Elbe/Weser, German Production in Weser/Ems, production of sour gasses via Emmen GZI, production of ‘Friese gassen’ via Kootstertille and production of offshore L gasses via the LoCal pipeline.

In general, production capacity of these fields is published on a yearly basis. In this research, it assumed that the difference between production in year $m$ ($t$) and the production in year $m+1$ ($t+365$) is covered linearly between the first days of the year. For example, production of source P1 in day 56 of year $t$ is implemented in the model as:

$$P_{1_{t+365}} = P_{1_t} + \frac{50}{365} \times (P_{1_{t+365}} - P_{1_t})$$

**Groningen**

For the production in Groningen, the NLOG predictions as presented in chapter 1.1 are used.

**German Production**

For the German Production, the numbers as presented in chapter 1.1 is used. The Wobbe of this production is assumed to be 46 MJ/m$^3$ on average.

**Emmen GZI**

In Emmen, the concessions of Sleen and Rossum are led to the “Gas Zuiverings Installatie” (Gas Treatment Installation) in Emmen. Gasses from these fields have large sulphide content and need to be treated before they can be injected in the GTS grid. Gasses from Emmen GZI have a higher Wobbe than L gases, but its Wobbe is too low for the H gas system.

**Kootstertille**

At Kootstertille, ‘Friese gassen’ are injected in the L gas grid: small fields with a low calorific value. Sometimes, the calorific value here is even below H gas. Fields connected to Kootstertille are Warffum & Marum, Tietjerksteradeel, fields within the Leeuwarden concession and Northern Friesland (incl Blija). Not all of these gasses are L gas. There is a small nitrogen production plant to lower the Wobbe in times of a relatively high amount of H gas.

**LoCal**


The production of these fields is relatively small, and if no other fields are explored production of these fields will decrease rapidly.
4.2.2 Nitrogen production facilities

Within the NWE L gas system, 5 nitrogen storage facilities exist. The daily production capacity of these storages is presented below. To place these numbers into perspective, in general one volume part of H nitrogen can be mixed with 6 volume parts of H gas in order to be of L gas quality. For modeling purposes, one mcm of nitrogen is assumed to have an energy content of 0.01 GWh as discussed in chapter 3.

4.2.3 Underground storage facilities

In the NWE L gas system, 7 Underground Storage Facilities (UGS) are installed. In general, an underground storage facility is either in a salt cavern, with a relatively low Working Volume but a high withdrawal capacity, or in a depleted gas field, with a high Working Volume but a relatively low withdrawal capacity. These two storages represent different functions within the system. This is implemented in the simulation tool by assigning different costs, as described in chapter 3.

Also described and validated in chapter 3 is the assumption that the gas quality within a UGS is constant over time. This assumed Wobbe is presented in Figure 4.1, next to the Working Volume, Injection capacities and withdrawal capacities. Capacities have been obtained from company websites (Epe RWE), Brattle report on flexibility (Brattle 2011) for EPE Nuon, (CIEP 2011) for Gournay, (WEG 2011) for Nuttermoor and Norg, Alkmaar and Zuidwending, including its expansion, from Gas Transport Services BV (2011).

<table>
<thead>
<tr>
<th>Calorific value</th>
<th>Working Volume</th>
<th>Injection capacity</th>
<th>Withdrawal capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJ/m³</td>
<td>mcm</td>
<td>GWh</td>
<td>mcm/day</td>
</tr>
<tr>
<td>PGI Alkmaar</td>
<td>36</td>
<td>500</td>
<td>5000</td>
</tr>
<tr>
<td>Norg</td>
<td>35,17</td>
<td>3000</td>
<td>29308</td>
</tr>
<tr>
<td>Epe Nuon</td>
<td>36</td>
<td>220</td>
<td>2200</td>
</tr>
<tr>
<td>Epe RWE</td>
<td>36</td>
<td>553</td>
<td>5530</td>
</tr>
<tr>
<td>Zuidwending</td>
<td>35,17</td>
<td>200</td>
<td>1954</td>
</tr>
<tr>
<td>Gournay sur Aronde</td>
<td>38</td>
<td>1280</td>
<td>13511</td>
</tr>
<tr>
<td>Nuttermoor</td>
<td>38</td>
<td>1069</td>
<td>11284</td>
</tr>
</tbody>
</table>

Figure 4.1 UGS facilities (L gas) within the NWE gas system and their capacities

For the production and withdrawal capacities the generic patterns published by GSE (2010) are used as there is no data available about the specific patterns for these storages. These patterns are shown in figure 3.2.

---

2 Capacities obtained from company websites (Epe), CIEP (2011). "Seasonal flexibility in the Northwest European Gas Market."

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4.2.4 Demand for L gas

In order to simulate the L gas system scenario's for demand profiles for the different quality areas supplied by L gas are assumed. This research makes use of data of the GTS website. GTS publishes hourly gas flows at border points at the GTS dataport. Also, German production numbers are published by WEG (see Chapter 4.2.1). Also, actual injection and withdrawal rates of Norg and Alkmaar are used. The data are transformed into datasets per region:

<table>
<thead>
<tr>
<th>Quality Region</th>
<th># of inhabitants</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern part of the Netherlands [N-NL]</td>
<td>1.717.729</td>
<td>11%</td>
</tr>
<tr>
<td>Ommen [Ommen]</td>
<td>6.487.140</td>
<td>39%</td>
</tr>
<tr>
<td>Western part of the Netherlands [W-NL]</td>
<td>6.219.801</td>
<td>37%</td>
</tr>
<tr>
<td>Middle part of the Netherlands [M-NL]</td>
<td>2.231.130</td>
<td>13%</td>
</tr>
</tbody>
</table>

Table 4. Number of inhabitants per quality region (based on CBS data and “Gasunie Kwaliteitsdocument”)

4.2.5 Other input data

As described in the preceding chapter, transport constraints are not included in this simulation tool. However, in the validation and verification phase some transport constraints appeared to be important in order to make the model work. One of the capacity constraints that is included is the pipeline capacity from Wieringermeer back to the North of the Netherlands. According to CE (2005) this capacity is 10,8 mcm/day. For modeling reasons, other transport constraints are put on the export stations at Oude Statenzijl. The capacity at this point has been set at 250 GWH/day, being the maximum flow over this point in 2011. For the Wobbe index of H gas, 51,6 has been assumed as the constant quality. This value has been deducted from dataport of GTS.
### Phase 1 Background: General functioning L gas system

**Input**
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH2)

**Output**
1. Concepts and definitions natural gas systems (CH2)
2. Basic understanding L gas system (CH2)
3. Main stakeholders and interests regarding gas quality (CH2)

### Phase 2 Modeling

**Input**
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach these objectives? (CH3)
3. How is this general modeling technique applied to the NWE L gas system? (CH4,5)

**Output**
1. General modeling approach (CH3)
2. Most order of supply sources (CH3)
3. Main system constraints (CH3,4)
4. L gas system components and capacities (CH4)

### Phase 3 Stakeholder behavior analysis

**Input**
1. What possible solutions are being considered among stakeholders and how are these solutions in terms of implementation? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPI's in the L gas system and how will stakeholders respond to changing KPI's? (CH6)

**Output**
1. Technical alternatives (CH6)
2. KPI's of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

### Phase 4 Integrated scenario analysis and conclusions

**Input**
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI's evolve in the different scenarios and how are stakeholders expected to respond? (CH8,9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH8,9)
4. To what extend did the chosen modeling technique approach meet initial requirements? (CH10)

**Output**
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH8,9)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH10)
4. Recommendations to Dutch government and EBN (CH11)
5. Reflection on modeling approach (CH10)
5  Designing the tool in software package Linny-R

After having introduced Linear Programming as a mathematical approach to model a natural gas network and after having specified the components and capacities of the NWE L gas system, these are combined into the design of a simulation tool in this chapter. In this research this LP problem has been formulated by means of a modeling software package. Chapter 5.1 introduces this software package and describes how the important aspects of the LP problem are incorporated in this package. Chapter 5.2 describes how these system components are put together in one simulation tool. Chapter 5.3 discusses the validation and the verification of the model. This chapter ends with a conclusion of the modeling phase in chapter 5.4

5.1  Modeling software Linny-R

The general LP problem as presented in chapter 3 does not yet meet the requirements set to the model. The number of constraints increases quickly when applying the chosen constraints to a large natural gas system like the L gas system and when using sufficient time steps. This reduces the workability and the accessibility of such a model. Also, calculating the objective function is to be done with solving software.

This research uses the software package Linny-R, developed at the TU Delft by Dr. P.W.G. Bots, associate professor at the faculty Technology Policy and Management and second supervisor for this research. This software package provides an attractive interface in which the constraints chosen can easily be implemented and adapted. Linny-R translates these values into all constraints in which this specific value is being used. Therefore, the user does not have to work in this list of constraints but only in the interface. Linny-R uses a solver to solve this LP problem.

This paragraph briefly describes the interface of Linny-R as this will enable the reader to understand the simulation tool that is designed and used in this research. Also, it shows how the 5 constraints and the merit order of sources are designed in Linny-R.

5.1.1  Products and processes

In Linny-R there are two types of nodes: products and processes. A process is denoted with a square. A product is denoted with an ellipse. Products are either the input or the output for a process. If this is the case, this relation is to be indicated with an arrow (see figure 5.1). For every node, the user has to provide information (see figure 5.2).
5.1.2 System constraints in Linny-R

In paragraph 3.3.1, 5 system constraints have been identified and mathematically described. This paragraph shows the representation of these constraints in Linny-R. The 5 constraints were:

1. Demand constraints
2. Production constraints
3. Storage constraints
4. Quality Constraints
5. The existence of physical connections

**Demand Constraints**

\[ P_1 + P_2 + P_3 = D_t \]

In order to model the demand constraints in Linny-R, the production nodes are connected to the demand node. At the properties of the demand node, the upper and the lower bound are set equal in order to make sure that the demand is satisfied at that time.
Production Constraints

\[ F_1 \leq C_1 \]

\[ F_1 \geq 0 \]

Production constraints in the simulation tool are modeled by setting the upper and the lower bound of the production process as can be seen in figure 5.3.
Storage constraints

The dynamic injection and withdrawal capacity of an UGS in the natural gas system is expressed in Linny-R by so called “dynamic bounds”, see figure 5.4. These dynamic bounds can be indicated in Linny-R, with the same pattern as shown earlier in figure 3.2:

\[
\frac{I_t}{I_{\text{max}}^t} = \left( \frac{S_t}{WV_{\text{max}}} \right) \times \left( \frac{S_{t-1}}{WV_{\text{max}}} \right)
\]

The storage level constraints are modeled in a different way. By setting the upper bound of a storage to its Working Volume and by indicating that this product is a buffer, the product can take the characteristics of an Underground Storage Facility.

\[
S_t = S_{t-1} + I_t - W_t
\]

\[
S_t \leq WV_{\text{max}}
\]

\[
S_t \geq 0
\]
Quality constraints

\[
\frac{P_1}{P_1 + P_2} Q_{P_1t} + \frac{P_2}{P_1 + P_2} Q_{P_2t} \leq Q_{\text{max}}
\]

\[
\frac{P_1}{P_1 + P_2} Q_{P_1t} + \frac{P_2}{P_1 + P_2} Q_{P_2t} \geq Q_{\text{min}}
\]

Figure 5.6 gives an example of a quality constraint as modeled in Linny-R. At the arrow the Wobbe-index for a certain flow is given in brackets. The other number reflects the conversion from GWh to cubic meters for this specific flow. In the product properties, the Wobbe-range of a specific quality area (see chapter 4) can be implemented.
Physical constraints

\[ I = \sum_{i=1}^{n} \psi_i P_i \]

With

\[ \psi_i = \begin{cases} 1, & \text{when } P_i \text{ is coupled to } I \\ 0, & \text{when } P_i \text{ is not coupled} \end{cases} \]

The physical constraints are modeled by the arrows as was already shown in figure 3.2.

5.1.3 Merit order of supply

In the modeling approach, the merit order of supply sources plays an important role. This merit order of supply is modeled in Linny-R by assigning virtual costs to every specific supply node according to its position in the merit order as can be seen in figure 5.7. Important to keep in mind is the difference in costs for a GWh and a cubic meter.

![Figure 5.7 Process properties, with within the red box the costs assigned according to the merit order of supply](image)

5.1.4 Model set-up

In chapter 3.4, the model set up has been described. This model set-up can be easily adapted in Linny-R in the chain properties diagram as reflected in figure 5.8.
The simulation tool

With the necessary constraints determined in chapter 3, and the main system components and their capacities for the specific L gas system in North West Europe satisfied, the simulation tool can be designed. This simulation tool is built up by applying the modeling of the constraints to the system description in figure 4.1. The total simulation tool is too large to present in a concise manner. As an example, the Northern part of the Netherlands within the model is presented in figure 5.9. In Appendix E1-E5, screenshots of other parts of the model are presented.
5.3 Verification and validation of the model

5.3.1 Verification

As described in chapter 1, a large part of the interviews conducted has been focused on the verification of the need for the model, the verification of the model assumptions and the verification of the model data.

All interviews have confirmed the theoretical merit order of sources as introduced in this research as the order in which the different sources within the L gas system are used. Some remarks that were usually heard is that sometimes it occurs that there is a surplus of H gas that need to be blended into the L gas system without the need for this blending from the merit order point of view. Although real number about these flows were not present. It assumed that this is a consequence of a non optimal use of the system and therefore this does not influence the merit order of sources.

Also, all gas system components and their capacities have been verified in multiple different interviews. Data about capacities and the functioning of the system appeared to be confidential and therefore not available for this research. By making estimations and verifying these estimations in stakeholder interviews, the current values reflect a valid representation of the actual numbers. Finally, the choice of leaving away small gas system components like relatively small border points has been the result of discussions during these interviews.

5.3.2 Validation

In the preceding chapters, a number of modeling choices have been discussed that are not per definition initially chosen. Some of the assumptions are the consequence of the validation of the model and insights during these iterative phases. These assumptions include:

- The choice for a negligible small energy content for Nitrogen flows
- The choice of GWh as metric unit instead of cubic meter
- Including the capacity constraints on the pipeline between Wieringermeer and Groningen
- Using 183 time steps as a look-ahead time
- Setting the storage level at its working volume at the beginning of the winter
- Modeling the production cap

When discussing the results of the simulation runs in chapter 8, some other validation steps are discussed. These validation steps are easier to explain when the graph concerning this validation step is presented.
5.4 Conclusions phase 2

The objective of the modeling phase was to develop a simulation tool that would address more complexity than the single point analysis but that is not as complex as other models within the industry. By choosing the system constraints carefully and by implementing a merit order of sources, this model has been created in a new software package that provides for a workable and accessible model. This model will be used in the remaining of this research in combination with stakeholder analysis as performed in chapter 6.

In this modeling study, the one main assumption underlying in the simulation is the assumption that: In a competitive market, the utilization of the prioritized source will be maximized before the next source on the priority list will be used.

This assumption drives the merit order of sources. In the simulation tool, this assumption is only lost when system constraints limit the availability of one of the cheaper sources before it is utilized to the maximum.

Behavioral constraints are not implemented in this modeling approach, and therefore this simulation explores the physical boundaries of the system when it is used optimally. Non-optimal behavior because of, for example, opportunistic behavior on TTF or with UGS stock, information asymmetries and others are not implemented in the simulation and therefore need to be addressed separately. In this research, these issues are addressed in the actor analysis in chapter 6 and in the evaluation of the Scenario Analysis.

A model is always only a simplification or an approximation of the reality. Modeling assumptions bias the outcome of the simulation. Therefore, a model is only useful if you are aware of this and of the impact that this might have on the results. In chapter 10, the limitations of the modeling approach and the limitations that are put on the model by modeling assumptions are discussed.

With the model being designed and presented, phase two of this research has ended. This discussed the technical-physical complexity of the system. The next chapter will elaborate on the third phase of the research, enhancing the socio-political complexity,
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Phase 1 Background: General functioning L gas system

**Input**
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH2)

**Output**
1. Concepts and definitions of L gas systems (CH2)
2. Basic understanding of L gas systems (CH2)
3. Main stakeholders and interests regarding gas quality (CH2)

Phase 2 Modeling

**Input**
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach these objectives? (CH3)
3. How is this general modeling technique applied to the NWE L gas system? (CH4/5)

**Output**
1. General modeling approach (CH4)
2. Main ordering of supply sources (CH4.1)
3. Main system constraints (CH4.2)
4. L gas system components and capacities (CH4)

Phase 3 Stakeholder behavior analysis

**Input**
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPIs in the L gas system and how would stakeholders respond to changing KPIs? (CH6)

**Output**
1. Technical alternatives (CH6)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

Phase 4 Integrated scenario analysis and conclusions

**Input**
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPIs evolve in the different scenarios and how are stakeholders expected to respond? (CH8/9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH8/9)
4. To what extend did the chosen modeling technique approach meet initial requirements? (CH10)

**Output**
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH9)
4. Recommendations to Dutch government and EBN (CH11)
5. Reflection on modeling approach (CH10)
6 Alternatives

In the preceding chapters, the technical functioning of the L gas system is described. Now, the physical gas system and its functioning are known. In this chapter, possible stakeholder behavior to mitigate the problems related to the decline in production capacity is discussed. This comprises the third phase of this research as introduced in the introduction. This chapter aims to answer the following research questions:

1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation?
2. What are the motivations for stakeholders to consider these solutions?
3. What parameters are important in describing the functioning of the L gas system?

In this research the focus is on the physical flows within the system and the balance between supply and demand. In this chapter, three alternatives are discussed that are related to maintaining this physical balance. The first two alternatives are derived from increasing the supply. The third alternative is related to decreasing the demand. At first, the choice for these three physical alternatives is elaborated on.

The supply of gas needs to fulfill two main functions. It has to provide for the total yearly demand and it has to provide for the production flexibility to deliver gas in times of peak demand. The total available volumes of L gas in known reserves are limited and declining. In order to increase the total yearly volumes, quality conversion of H gas to L gas is the alternative for stakeholders within the L gas system to maintain production levels. The quality conversion capacity can be increased by building extra nitrogen production capacity within the system. This alternative reflects the first main function of natural gas supply. The second function is represented in the second alternative in this chapter: Increasing the flexibility within the L gas system.

The third alternative that is discussed in this chapter is related to decreasing the demand for L gas. This decrease can be obtained both actively and passively. Stakeholders within the L gas system can actively decrease the demand for L gas by converting L gas grids into H gas grids. This alternative is described extensively in chapter 6.3. Decreases in demand that are not influenced by the stakeholders within the L gas system are introduced in chapter 7, where demand profiles are designed.

This chapter introduces the three alternatives described above. For every alternative, the technology, the economics and the stakeholder preferences to these alternatives are discussed. As these alternatives are general changes in the physical balance, these changes can be obtained in multiple ways. These are discussed in this chapter. After having discussed the considerations among stakeholders towards these three alternatives, this chapter ends with the identification of the key performance indicators for the L gas system. These
performance indicators will be monitored in the remaining of this research and reflect the preferences of the stakeholders within the L gas system, thereby influencing their behavior towards one of the three alternatives as discussed in this chapter.

6.1 Increase Nitrogen production capacity

Adding nitrogen to H gas is discussed as a means to produce L gas from H gas. Increasing the nitrogen production capacity would increase both the ability of the system to satisfy peak demand and the availability of total volumes of L gas throughout the year.

6.1.1 Technology

In the L gas system, the main nitrogen production locations are in IJmuiden, Ommen and Heiligerlee. Nitrogen is produced in Air Separation Units. This production process needs a temperature of about -200 degrees Celsius. Therefore it takes a lot of energy to produce nitrogen. The start-up time is large, about one week, because the system needs to be cooled down and this needs to be done gradually to control the shrinking of the different components caused by the temperature drops. Therefore, nitrogen production generally cannot be easily switched on and off.

6.1.2 Allocation of Quality Conversion costs

The Netherlands

With the disappearance of a quality label on the TTF, GTS has become responsible for facilitating the required amount of quality conversion capacity in the Netherlands (Kerstholt and Israels 2011). Before that, every shipper was responsible for balancing the gas quality of its own portfolio. If one shipper would buy 3 mcm of L gas and 2 mcm of H gas, and then sells 5 mcm L gas, this 2 mcm imbalance would have to be compensated for by booking quality conversion capacity at the shipper's costs. Now, quality conversion costs are socialized among all consumers and accounted for in the transportation costs of gas, and it is the task of GTS to maintain the quality in the network.

This means that this role is now centralized at one place, thereby increasing the efficiency and the coordination of this task in the system. It appears that the introduction of socialization of conversion costs has led to a decrease in nitrogen use. Reversed Quality Conversion (RQC), the virtual conversion of L gas to H gas by compensating for imbalances in the other direction, is used by GTS to maintain the balance between H gas and L gas without using nitrogen (Heren 2008). In other words, the total gas system's imbalance is often smaller than the sum of individual imbalances.

The costs of performing this task are socialized among all consumers of gas within the Netherlands, so shippers no longer have their own quality conversion costs. Over 2012, the non-corrected quality conversion tariff is set at
€1,126/m³/hour/year and is included in the entry/exit tariffs set by GTS (GTS 2012)\(^3\). This fee is equal for all entry- and exit points within the Dutch gas infrastructure, regardless of the quality label at this point. To put these costs into perspective: the exit tariff at export points to Belgian was in a range of €22,18/m³/hour/year (Zandvliet H) to €30,75/m³/hour/year (Zandvliet L) in 2010.

The disappearance of the quality label has led to a significant increase in the liquidity of TTF. A liquid TTF is valued by both customers and policy makers as it allows for competitive pricing and a competitive advantage for TTF to other European gas markets.

**Germany and Belgium**

Between April and October 2011, the German gas market went from six separate market zones – three for H-gas and three for L-gas – to one with just two cross-quality areas, both combining H-gas and L-gas (Heren 2012). At NetConnect Germany (NCG) and GASPOOL, the two hubs in Germany covering the cross-quality

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\(^3\) The tariffs for contracts concerning 2012 and 2013 include a reduction due to the repayment ("verrekening verleden"), that results from the new regulatory system that has been decided upon by the Dutch regulator (NMA, JB). The repayment is based on the period 2006 – 2011. The repayment effect is valid for transport, balancing and quality conversion per network point* (GTS 2012). The actual contribution of the QC component in the GTS tariffs is €0,261/m³/hour/year, because the non-corrected €1,126/m³/hour/year is corrected by this discount of €0,865/m³/hour/year.

---

![Figure 6.1 Schematic overview of the conversion fee on NCG, a cross quality zones in Germany (NCG 2011)](image-url)
area, there is a quality conversion fee that should reflect the market value of quality conversion. The working of
this conversion fee is schematically reflected in Figure 6.1 and works the same for both NCG and GasPool.

When a shipper or a trader cannot balance its portfolio on quality, it has to pay for its imbalance. This price is paid
to the hub operator and reflects the costs of quality conversion. In April 2012, this fee was €1.95/MWh at
GasPool and €0.90/MWh at NCG. Market participants have generally welcomed any fee cuts, but still consider
€1.95/MWh too high. According to Heren (2012), the main obstacles for liquidity of the German market as
experienced by market participants are conversion and transaction fees. Heren (2012) states: “Sources said
€0.50-1.00/MWh was a reasonable charge for the conversion. BNetzA is currently moving towards approving
general rules requiring a gradual phase-out of the conversion fee, which includes the elimination of the charge
within four years by lowering it every six months.”

In Belgium, the balancing regime is still comparable to the Dutch regime before 2009: Shippers and traders have
to book capacity at the Nitrogen production locations in Lilo and in Loenhout to compensate for their
imbalances. Buying Dutch gas, with the quality conversion paid for at the exit point, is cheaper, because the
conversion component in these costs is socialized among all Dutch consumers of gas (CREG 2010). In Belgium,
shippers do have to balance their portfolio on quality, but for importing gas this is no longer necessary. So,
Belgian shippers can buy H gas in the Netherlands and import it as L gas into Belgium.

The importance for the ministry of Economic Affairs of a strong TTF compared to other hubs has been
discussed. Considering the quality conversion regimes at competing hubs like ZeeBrugge in Belgium and NCG
and GasPool in Germany, the current Dutch regime gives the TTF a competitive advantage. For the German
market, the regime is expected to follow the Dutch balancing regime in four years. A second important value for
the Dutch Ministry of Economic Affairs is the competitiveness of L gas. In this perspective, the phase out of the
conversion fee in Germany strengthens the position of L gas in Germany. Currently, the conversion fee is
regarded as a market barrier by market participants and it leads to price differences between L gas and H gas.
As will be shown in the remainder of this chapter, these price differences have the potential to make L gas
consumers shift to substitutes, like H gas.

6.1.3 Investment incentives

In the current Dutch regime, shippers and traders do no longer have an incentive to invest in nitrogen capacity as
they no longer carry the costs of this conversion themselves. Since GTS is responsible for having sufficient
quality conversion capacity, this would be the only stakeholder with a financial incentive to invest in increasing
nitrogen capacity, in addition to nitrogen producers who could sell their capacity to GTS. The decision whether
GTS is allowed to include its costs for quality conversion in the transport tariffs lies at NMa, the Dutch regulatory
body. NMa assesses the usefulness and necessity of the investment, and it assesses the effectiveness of the
investment when the asset is taken into use. The return for GTS is regulated in the “methodebesluiten” by NMa,
as stated in the Dutch natural gas law (“Gaswet”).

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From interviews with stakeholders in Germany and Belgium, it appeared that building new nitrogen production facilities is not considered a serious option there. The main reasons for this are the different regimes regarding quality conversion, making the investment riskier compared to the Netherlands, and the Dutch balancing regime that obliges GTS to have sufficient conversion capacity available for the existing contracts. As the costs for GTS are socialized among all Dutch users of gas, including the H gas users, this is cheaper than to produce nitrogen itself (CREG 2010).

In Germany, nitrogen production is considered to be a commercial activity for TSOs by BNetzA. With the decreasing quality conversion fee at German hubs, German TSOs consider it to be more attractive to buy L gas at TTF and to transport it to Germany than to make a risky investment in a new nitrogen production plant without the support of a regulator to socialize the costs involved.

In Belgium, comparable incentives exist. With the disappearance of a quality label at TTF, Belgian shippers no longer have to balance their portfolio on quality. When total volumes of L gas are not sufficient anymore, other alternatives are considered to be more attractive to both CREG and Fluxys (Fluxys 2012). These other alternatives are discussed further in this chapter.

6.1.4 Costs of nitrogen production

Initial investment costs for a new nitrogen production plant with a capacity of 150,000 m$^3$/hour are estimated to be between 40-80 million Euros. This is only the investment for the production facility. Additional investment will be necessary in pipelines and in some cases storage capacity. In general, the depreciation time is 10-15 years. That means that roughly €5 million is depreciated yearly, averaging both ranges.

Also, operating costs are significant, with the electricity use of the compressor being the main contributor. GTS could deliver this energy in the form of natural gas. Reliable data regarding the operational costs of nitrogen production has not been found. The only indication of operational costs found refers to minimal operational costs of $0.11 per 100 cubic feet (~ 3 m$^3$) for large scale on site production (Humphreys 2012). This price would include maintenance and energy. Considering that nitrogen production for a natural gas system will not be operated most efficiently because of fluctuating production rates and relatively old facilities, this research uses €0.05 / m$^3$ as a very rough estimation of the operational costs of a nitrogen production location.

The costs are also dependent on the synergies that can be achieved. In the technical process, not only nitrogen is produced but also oxygen and other elements. The residual products might be of interest for industrial partners, thereby reducing the costs for nitrogen.

6.1.5 Design variables

There are different options for GTS to organize nitrogen production. Four main variables are:

1. Production capacity
2. Inclusion of nitrogen storage

3. Contracting schemes

4. Location

In the current system, three different ownership structures for GTS are in use. In Ommen, GTS owns and operates its own nitrogen production facility with a large capacity. In Heiligerlee, GTS owns a production facility with a relatively small capacity, but with a nitrogen storage facility in which nitrogen can be injected. The withdrawal capacity of this storage is relatively big. This design covers for the start-up time and the low utilization rate of nitrogen production facilities. Finally, in IJmuiden, GTS does not own the production plant, but GTS buys capacity from a local producer. Linde Gas operates an Air Separation Unit that produces large amounts of oxygen for Tata Steel. With Nitrogen being a residual product, this facility runs throughout the year and therefore the start-up time is not an issue for this plant. If there is no demand for the produced Nitrogen it is released into the air. The downside of this design for GTS is that it pays for the booked capacity even if there is no demand for Nitrogen.

As discussed before, new nitrogen production facilities are considered as a serious option in the Netherlands only. New locations would need to be relatively close to blending stations to be blended into the L gas system. Ommen and Wieringermeer, being the most important blending stations, already have nitrogen production connected. Because of the function of these stations in the system, increasing capacity at those points would make the most sense. The presence of industrial activity in the vicinity would make it easier to create synergies and therefore costs reductions. These considerations limit the possible locations for new nitrogen production facilities.

6.1.6 General considerations among stakeholders

Among stakeholders, nitrogen is not considered as a sustainable solution for the long term. However, as described in the report of KEMA and Kiwa (2011), the costs of other alternatives decrease rapidly if the time at which these alternatives are implemented can be postponed. Therefore, nitrogen production is seen as a means to postpone the investments in other alternatives. Also, an investment in a nitrogen production facility is not as complex as other alternatives. The roles in this process are clear, as are the technologies and the allocation of costs.

The reasons why it is not considered a sustainable solution on the long term by all stakeholders are threefold. At first, it might be costly in the long run to artificially maintain the L gas market by continuously diluting H gas with nitrogen. It would increase the conversion costs within the Netherlands, thereby putting pressure on the acceptance of the socialization of conversion costs. To compensate for the expected decline, every year
roughly 100,000 m³/hr extra nitrogen production capacity would have to be built.\footnote{Considering the blending ratio of 1:6, this would compensate for a decrease in production capacity of 16.8 mcm/day, which approximates the decline in L gas production per year in Figure 1.2 and figure 1.3 combined.} It seems to be contra intuitive to maintain an L gas system with a too large demand for the gas that is produced over a longer period of time.

Utilization of the to-be-build nitrogen capacity is expected to be relatively low; generally nitrogen is mainly used for peak demand. Besides the economic viability of such an investment, the large area this facility would need and the environmental impact of such a new facility puts questions on the desirability of this alternative.

6.2 Increasing production flexibility within the system

In order to provide for the flexibility in the system, Brattle (2011) has identified the main physical sources of flexibility within gas systems: gas storage, production flexibility, import flexibility, line pack and interruptible demand. In this research, only gas storage is taken into account as an adjustable component. Line pack, which is the flexibility resulted from a pressure drop in pipelines, is relatively small in the small and dense Dutch infrastructure and is also mainly used on an hourly basis, while this research makes use of a daily time step. Interruptible demand and import flexibility is mainly used in the H gas network. Interruptible demand cannot be used at households, which are the main consumers of L gas. Import flexibility is not applicable because all imported gas within the Netherlands is H gas. Finally, production capacity is considered to be a given in this research, and therefore it cannot be regarded as an alternative to be adjusted by stakeholders within the system.

6.2.1 Technology of gas storage

During low demand days, typically in summertime, the Groningen field is producing on a sub optimal rate. The peak demand hours in wintertime are the bottlenecks in the production of L gas flexibility demand. By increasing the flexibility of the system, these capacity problems could be mitigated.

To balance between this swing in demand, Underground Storage Facilities (UGS) are installed in natural gas systems. A UGS is a depleted gas field or an empty salt cavern in which gas can be stored in times of low demand. This gas can be withdrawn in times of high demand, thereby adding to the flexibility of the system. At this moment, there are a number of UGS in operation in the NWE L gas system.

6.2.2 Investment costs and incentives

Investment in extra storage capacity will add flexibility to the system and it will help to be able to provide gas during peak demand hours. UGS has been identified as a commercial activity and investment is usually done by private parties. The incentive for an investment in storage capacity is the price difference for gas between summer and winter. Gas is bought at a low price, for example in the summer, stored in an UGS and sold in times of peak demand, when the prices are generally higher.
The main components contributing to the initial investment are cushion gas, injection and withdrawal facilities and in case of salt caverns mining activity (Evans and Chadwick 2009). Most of the times the pipeline connection to the grid is still in place, since the storage facility was used to produce gas initially. The main operating costs are energy use for compressors. For this research, the exact costs are not relevant as it is a commercial activity and therefore its costs will not be put down on end consumers.

6.2.3 Design variables
The two types of storages are salt caverns, with a relatively small working volume but a large and flexible withdrawal rate, and depleted fields or aquifers, both with a relatively high working volume but lower injection and withdrawal rates.

The gas that is stored can either be pure Groningen gas or H gas diluted with nitrogen. Groningen production is characterized by seasonal fluctuations and extra storage capacity would flatten this pattern. This would increase the yearly production of Groningen gas and thereby its value for the shareholders. Those shareholders ideally see the Groningen field’s production at a load factor close to 1. The load factor is a parameter that divides the total realized yearly production by the technically maximum hourly production. A UGS makes it possible to come closer to this ideal load factor.

6.3 Partial transition of L gas networks to H gas networks
With L gas supplies decreasing in volume while there is enough supply of H gas, an option is to switch consumers from using L gas to using H gas. This would lower the total demand for L gas in North West Europe and therewith it could potentially delay problems regarding the balance between supply and demand. However, this transition is a complex process as will be discussed in this chapter.

6.3.1 Technology
When consumers are to be switched from L gas to H gas, their gas burning appliances should be adjusted to the new quality. As all gas burning appliances are set to a specific gas quality, this quality cannot just be changed. The main difference between H gas and L gas is its calorific value, being the energy amount per volumetric unit. As all hydrocarbons need a total combustion to avoid toxic CO emission and/or flame instabilities, the oxygen inlet is adjusted to this energy content.

When a different gas quality is provided, every gas burner has to be adjusted to this new quality by changing the oxygen inlet in order to ensure a safe burning process. Therefore, gas exit points need to be disconnected from the grid, and trained specialists need to change every appliance in every household before the exit point can be reconnected. Sometimes this change would be replacing a sprinkler; sometimes changing the air inlet can be done easier. In general, old appliances would need more work to be adjusted compared to relatively newer appliances (Kema, Kiwa et al. 2011). With the safety hazards related to this process in mind, it should be ensured that every gas burning appliance is adjusted before the exit point is reconnected. Therefore it is recommended that his process has to be coordinated and monitored closely.
There is a number of technical ways to make this change from one quality to another. The safest way is to do it in small steps, where the gas quality changes in margins of 5%, thereby allowing the machines to be in the safe bandwidth (of 5%) at all time. This 5% bandwidth is in line with the current gas specifications in the Netherlands, so all appliances can safely burn gas within this quality range. By adjusting the air inlet to the upper bound, which will be the lower bound of the new gas quality, one can gradually increase the energy content of the gas while staying within the safety margin. However, this stepwise process requires multiple disruptions in gas provision.

Adapting the burners at once might lead to larger safety hazards and machines might not be able to handle this abrupt change. However, the gas disruption is limited to a one day disruption. At all times, a trained specialist need to get in every house to adapt all appliances. It should be assured that every household within the specific region is visited before the region is reconnected.

At the 1st of January 2016, a new emission regulation within the Netherlands will be entered into force. By this new regulation, recently implemented strict emission limits are put on existing gas burning appliances as well. In the interview at Zantingh BV this moment is identified as a moment at which many consumers will have to replace their appliances. In order to avoid these consumers to replace their equipment twice within a short notice it is important that the new appliances are adjusted to the future gas specifications. Therefore, these specifications must be set before this time.

6.3.2 Design variables

When describing the transition as changes in the physical flows within the system, there are 2 main variables in the design of this transition. These variables are the order of the transition and the speed of the transition.

The order in which the transition takes place has consequences for the system's performance. One can decide to enforce transition in Germany, Belgium and France first, or to start the transition in the Netherlands. Transition in the Netherlands might be an instrument for the Dutch government and other Dutch stakeholders, while transition in foreign countries is harder to control, but would also give the chance to delay the transition within the Netherlands, thereby reducing the costs for Dutch society.

When starting the transition in the Netherlands, one could decide to start in the south or in the north. The north would be closer to existing H gas pipelines with enough transmission capacity to accommodate the increase in H gas demand, whereas the south would make more sense because the main source of L gas is in the north.

The third option to consider regarding the order of transition would be to make the transition per end user instead of per region. To achieve the same decrease in demand, it might be easier to adapt one large industrial consumer than multiple households.

In order to be able to make this transition, specialized personnel need to be trained. Therefore, the speed at which the transition can take place is limited, as the costs of this training need to be controlled. Also, the
transition is to be made in times of low gas demand to avoid interruptions in gas supply during cold winter months.

6.3.3 Investment costs and incentives

In 2011, Kema and Kiwa executed a research commissioned by the Dutch Ministry of Economic Affairs, named “Gaskwaliteit voor de Toekomst” (2011). In this research, they investigated the costs of a transition in the Netherlands. According to their estimates, the costs of a transition decrease drastically if this transition is postponed (see figure 6.2). These estimates are based on the fact that postponing the transition will lead to a natural phase out of older appliances that cannot be easily adjusted to another gas quality. In the same report, the costs per household are estimated to be €150.

<table>
<thead>
<tr>
<th>Year</th>
<th>Costs of transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>€2.6 – 5.7 billion</td>
</tr>
<tr>
<td>2025</td>
<td>€2.7 – 2.8 billion</td>
</tr>
<tr>
<td>2030</td>
<td>€0.8 – 0.7 billion</td>
</tr>
</tbody>
</table>

Figure 6.2 Costs of a transition in the Netherlands according to Kema and Kiwa’s “Gaskwaliteit voor de Toekomst”

Based on this large decrease in costs over time, the first network that is converted would be converted at higher costs than the following networks. Therefore, there is no incentive for customers or regional Distribution System Operators to take the first step. Next, as seen in the technical description, a transition is an intensive and complex process with large safety hazards. There does not seem to be an incentive for private parties to start this transition, and after the liberalization of gas networks there is not one strong party like the old Gasunie within the system that could coordinate this process. Therefore, it is recommended that the national governments should take a central coordinating role.

The allocation of costs is also a difficult matter. Consumers do not have much of a choice in this matter but they will have to pay for the transition of their grid in the end. This will not be in favor of the reputation of natural gas as a cheap and reliable source of energy. Therefore, the gas industry, including EBN, should monitor this transition and the costs need to be managed well where possible.

6.3.4 Considerations among stakeholders

For the producers of L gas, this transition might be risky as it decreases the demand for the gas it produces. On a small scale, this might be necessary to maintain the match between physical demand and supply. But when it would happen too soon and too quickly it might reduce their benefits from the gas they produce. Therefore, timing is of the essence in this option.

6.4 Viewpoints of countries in NWE regarding alternatives

In Belgium and Germany, a gradual transition to H gas is considered to be the only alternative for a decrease in L gas demand. There are no incentives to invest in nitrogen production there. As both countries don’t have their
own production, they consider storage not to be an option either. This leaves a transition to H gas as the only viable option. In France, the supply of L gas is not on the political agenda. Their demand is secured in long term contracts with GasTerra until 2028 so that gives them no reasons to worry. In Germany and Belgium, some demand is covered in long term contracts too, and thereby guaranteed by GasTerra, but also a significant part is bought on the spot market.

6.4.1 Belgium
Belgium has converted some areas from L gas to H gas in the 1970s and the 1980s and therefore, it has little experience with this process. Next, the Belgian regulator CREG published a report in 2007 in which a detailed plan for a large scale transition was presented (CREG 2007). At that time, CREG did not want to be dependent on GasTerra being the single supplier of L gas. Thanks to the disappearance of the quality label on TTF, H gas has become a substitute for L gas and CREG delayed their plans for a large scale transition (CREG 2010). They expect the amount of L gas available from the Netherlands to remain at the same level for the foreseeable future.

In Belgium, the demand for L gas is still growing, in contrast to the Netherlands and Germany. The reason for this is that the number of houses that is connected to the grid still increases. Historically, this increase in demand is 1.5% per year. Because of limited interconnector capacity at the border point of Hilvarenbeek, Dutch imports cannot meet this increase in demand. Therefore, it is planned to convert smaller industries to the H grid to compensate for the growth in demand. As industries have a flat demand pattern this would lower the capacity congestion at Hilvarenbeek. Next, a small pilot (3000 households) for a residential transition is planned in order to get experienced in these transition projects. This process has been described extensively by Fluxys in their presentation to their end users on the 9th of May 2012 (Fluxys 2012), page 130 to 160.

6.4.2 Germany
Also in Germany there is little experience in converting L gas grids to H gas grids. Small residential areas in Nordhorn and in Hannover have been converted in the last decade. These were local initiatives for two particular reasons and not centrally organized transitions to cover for a decrease in L gas supply. One area, in Nordhorn, made this switch for commercial reasons as a competing H gas TSO could provide better prices. In a small area in Hannover, the transition was made because the small local field that provided for this gas was depleted.

In Germany, the transition is technically less complex for two reasons. At first, Germany has a wider Wobbe range for the L gas, which has an overlap with H gas. In chapter 6.3.1 it has been described that a stepwise transition of 5% each would be safest. In Germany, the quality range of L gas (Wobbe: 37.8 – 46.8 MJ/m³) overlaps with the quality range for H gas (46.1 – 56.5 MJ/m³) (DVGW 2012). This means that gas burning appliances in Germany are designed to handle a wider range for the Wobbe index and therefore the transition can occur safely without having to use multiple steps.
The German TSOs presented their outlook for the requirements for the network in the next 10 years in “Netzentwicklungsplan Gas 2012”. In this document, the TSOs expect the total balance of L gas in Germany to be insufficient within 10 years (see Figure 6.3). Therefore, optimally speaking local imbalances that might arise early are not solved by increased transport capacity to these local markets but transition to H gas grids is preferred. Therefore German TSO’s see small scale transition to be inevitable on the medium term. However, given the complexity as discussed in this chapter, the speed at which they can make the transition is limited. For now, the German TSOs have the plan to compensate for the decrease in German L gas production and to maintain the current level of imports from the Netherlands. They do not expect a decrease in available L gas from the Netherlands within the next 10 years. To convert grids at a speed that compensates for the decline in

![Figure 6.3 Total balance of L gas balance in Germany. speicher = storage; bedarf = demand. Source: (Netzentwicklungsplan 2012)](image)

If there would be a partial transition in Germany, the following criteria are identified based on interviews that determine what areas would be the first ones to make this transition:

1. At the borders of the system
2. Area provided by German L gas
3. H gas transmission network nearby

4. Competing H gas TSO nearby

6.4.3 The Netherlands

Concluding the preceding, it can be stated that Belgium, France and Germany do not expect that the L gas supply from the Netherlands will decrease in the foreseeable future. In the Netherlands, the EDGaR studies are commissioned by the government to investigate the term at which the L gas specifications can be the way as they are now. The expected outcome of these studies is an advice to maintain the current specifications until 2030 and to postpone transition until that point in time.

If the Dutch policy is to avoid a large scale transition in the Netherlands, it can either build extra nitrogen capacity, build extra storage capacity, or gradually decrease the amount of L gas available for exports in the long run. Neighboring countries will need time to prepare for this decrease. This time is necessary to train personnel, to set up and organize the transition and to gain experience with the process of a transition. Transparency about the perspectives for available L gas for export is therefore important to make this transition fluent.

6.5 Summary stakeholder analysis

In the preceding chapters, the preferences and considerations of stakeholders regarding the three alternatives are discussed. In table 6.4 these are summarized and valued for all 7 groups of stakeholders as identified in the introduction.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Stakeholder</th>
<th>Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase</td>
<td>Competition authorities</td>
<td>- + Might avoid excessive costs of grid conversion</td>
</tr>
<tr>
<td>Nitrogen</td>
<td></td>
<td>+ Liquidity of TTF important for market</td>
</tr>
<tr>
<td>production</td>
<td></td>
<td>- Only allows it if long term efficiency and usefulness</td>
</tr>
<tr>
<td>capacity</td>
<td>Dutch government</td>
<td>+/- Could delay large scale transition of grids (and costs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Might be necessary to maximize profits from Groningen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Temporary solution, not a sustainable one</td>
</tr>
<tr>
<td></td>
<td>Manufacturers</td>
<td>+ Makes it possible to maintain small bandwidth</td>
</tr>
<tr>
<td></td>
<td>Traders and shippers</td>
<td>- - Don't want any increase of QC component in tariffs</td>
</tr>
<tr>
<td></td>
<td>Downstream</td>
<td>- + Delays costs of transition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Price increase in GTS tariffs; also for H gas users</td>
</tr>
<tr>
<td></td>
<td>Midstream</td>
<td>- - Adds complexity to its task of quality control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Investment risk of nitrogen production; low profitability</td>
</tr>
<tr>
<td></td>
<td>Upstream</td>
<td>++ + Maintains the market for varying gas qualities</td>
</tr>
<tr>
<td></td>
<td>competition</td>
<td>++ + Alternative with the least market interference</td>
</tr>
</tbody>
</table>
### Performance Indicators for the L gas system

This chapter concludes with determining the key performance indicators of the L gas system, based on the stakeholder preferences that have been put forward in this chapter. These key performance indicators will be evaluated in the scenario analyses later in this research. The KPI have been derived from the analyses performed before. They reflect the important technical parameters of the system at which the stakeholders base their investment decisions upon. The main performance indicators are:

- the need for extra nitrogen capacity

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- the production pattern of Groningen production
- the use pattern of H gas for blending
- the conversion costs
- the usage of storage facilities

6.6.1 Investment in extra nitrogen capacity and development of conversion costs

The first variable that will be looked into is the occurrence of the imbalance between demand and supply in the scenarios. This is modeled in such a way, that this imbalance is solved by using non existing nitrogen facilities, as described in chapter 7.2.2. If this occurs, it is interesting to see when this happens, how much nitrogen is used, and with what pattern this nitrogen is demanded.

These three variables of extra nitrogen capacity determine what investment model would fit best. If there is only a demand for a small number of peak days, a nitrogen storage combined with a small production location would be the best investment model. If there is a need for extra nitrogen, but only for a small number of years, so a temporarily peak in nitrogen demand, it would not be advisable for GTS to invest in an own nitrogen plant, but contracting capacity on an existing plant, would be favorable. This is the model that is currently used in Ijmuiden. Finally, if there is lasting demand for extra nitrogen with a relatively stable pattern of use and prolonging for multiple years, the construction as used in Ommen would be recommended, in which GTS constructs, builds and operates its own nitrogen production facility. Because of the high start-up time and costs, this facility should run for a longer period of time.

Next to the demand for extra nitrogen, also the usage pattern of the existing nitrogen facilities is interesting to monitor. The costs of these facilities are socialized over all customers of gas in the Netherlands, regardless of the quality of the gas they use. These conversion costs have been identified in stakeholder analysis as a catalyst for a rapid transition of L gas grids to H gas grids. High nitrogen usage in a scenario with slow or no transition might therefore not be a scenario that is plausible.

As a conclusion, the main questions to be answered regarding nitrogen usage are:

1. Extra nitrogen capacity:
   a. When?
   b. How much?
   c. What model?
   d. Location?
2. Current nitrogen capacity
   
a. Patterns of use

6.6.2 Production pattern of Groningen production

Groningen production pattern is an important system performance indicator. GasTerra has set its goal to maximize the value of the Dutch small fields and the giant Groningen field. The Dutch government receives, by means of the MOR and State participation in GasTerra and EBN over 85% of the Groningen gas value.

A value deducted from the principle of Net Present Value has been used as a means to express the value of early production compared to production in a later year. The production in any given year has been discounted with a discount rate of 3% per year in comparison to 2011, against a vast price of €0.25/m³. The higher this value is, the higher the ‘real value’ of the overall production. This NPV is calculated for every scenario.

For all scenarios, the Groningen sales targets for GasTerra are evaluated and the implication of the production pattern is discussed.

6.6.3 Use of H gas for blending

Although H gas is assumed to be unlimited available in this research, there are implications for the use of H gas. By analyzing these patterns of use, these implications are analyzed.

High peaks of H gas blending might indicate that additional investments in H gas capacity are necessary to be able to transport this H gas. Large investments in extra H gas capacity might be indicators that the scenario is not very plausible, as it would increase the incentives to speed up the transition. As discussed earlier, a typical gas system has to provide both commodity and flexibility. When Groningen does not longer deliver the flexibility, some other source has to deliver this flexibility. If H gas is to be this source of flexibility, this would imply large investments.

The use of H gas might have implications for the merit order of sources. As H gas diluted with nitrogen can be seen as a substitute for L gas, the need for extra H gas capacity would increase the market share of this competing gas. An increase of market share has implications for GasTerra. Being the main producer of L gas at this time, it has a lot of information about the market and it is a key player in the market. An increase of H gas in the total L gas system has the potential to weaken this position. For example, a large importer of H gas could demand an off take guarantee in exchange for the large investment it has to take to provide sufficient H gas for blending. These are important considerations to take into account. However, as GasTerra is also the main trader in H gas in the Netherlands, this impact might be limited.

Concluding, from the use pattern of H gas the following questions are to be answered:

1. What peak H gas capacity is needed to balance supply and demand?
2. How does this compare to other scenarios?

3. What is the demand for flexibility of H gas delivery?

4. How does the market share of L gas evolve?

6.6.4 Utility of Storage facilities and options for investment

A final important performance indicator of the system is the utility of storage facilities. Storage facilities play an important role in providing flexibility to the system. As described earlier, it is indicated as a commercial activity in the “Gaswet” and therefore it is interesting to evaluate whether investment in storages are likely to occur. It can be assumed that investments in UGS are likely to appear when there are large fluctuations in H gas demand for blending, or when Groningen production is not producing close to Load Factor 1 over a longer period of time, while production capacity is a limiting factor at days with high gas demand.

6.7 Conclusions phase 3

After this chapter, the third phase of the research comprising the socio-political complexity has been finalized. This has resulted in a systematic overview of the three physical alternatives considered in the L gas system to balance supply and demand under the decline of L gas production capacity. Key performance indicators have been identified, and stakeholder preferences towards both the alternatives as the KPI are described.

Now both complexities have been described separately in the preceding chapters, both analyses are integrated in order to evaluate the developments in the L gas system.
### Phase 1 Background: General functioning L gas system

**Input**
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH4.3)

**Output**
1. Concepts and definitions natural gas systems (CH2.1)
2. Basic understanding L gas system (CH2.2)
3. Main stakeholders and interests regarding gas quality (CH4.3)

### Phase 2 Modeling

**Input**
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach these objectives? (CH3)
3. How is this general modeling technique applied to the NWE L gas system? (CH4.3)

**Output**
1. General modeling approach (CH3)
2. Model order of supply sources (CH4.3)
3. Main system constraints (CH4.4)
4. L gas system components and capacities (CH4)

### Phase 3 Stakeholder behavior analysis

**Input**
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH6.5)
2. What are the preferences of stakeholders towards these solutions? (CH6.5)
3. What are the KPI in the L gas system and how would stakeholders respond to changing KPI? (CH6)

**Output**
1. Technical alternatives (CH6)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

### Phase 4 Integrated scenario analysis and conclusions

**Input**
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond? (CH8.3)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH8.9)
4. To what extent did the chosen modelling technique approach meet initial requirements? (CH10.0)

**Output**
1. B policy responses and 4 demand profiles in 20 scenarios (CH7.1)
2. Evolution of KPI in 20 scenarios (CH8.3)
3. General trends in the L gas system (CH9.1)
4. Recommendations to Dutch government and EBN (CH11.1)
5. Reflections on modelling approach (CH10.0)
7 Scenario Design

After finalizing the third phase of the research by identifying the stakeholder preferences towards the technical alternatives considered within the industry, the two types of complexity are integrated in the fourth phase of this research. In this fourth phase, the model as presented has been used to evaluate future scenarios for the North West European L gas system. This chapter elaborates on the design of 20 future scenarios. This chapter aims to answer the following research question:

1. What possible future scenarios for the L gas system can be designed?

For the design of scenario, a difference has been made between active changes in demand and supply, and passive changes in demand. Active changes in demand are changes that can be directly influenced by the Dutch government or by other main stakeholders in the system, like GTS or TSOs in Germany, Belgium and France. These active changes are referred to as Policy Responses. Passive changes reflect changes in demand because of changing energy needs per customer. These are referred to as demand profiles.

The parameters used to design these assumed scenarios are shown in figure 7.1. Chapter 7.1 sets the demand profiles. Here, L gas demand is split up in a temperature related part and a temperature unrelated part. Changes in these parameters form 4 demand profiles. In chapter 7.2, a transition pattern is split up in the order of the transition and the speed of this transition. Combining these variables leads to 5 Policy responses.

![Diagram of scenario design](image)

Figure 7.1 This chapter combines 5 policy responses and 4 demand profiles into 20 future scenarios
7.1 Demand profiles

A well functioning L gas system should be able to provide different possible demand profiles. In this chapter, 4 demand profiles are developed. There are numerous external developments that influence the demand for L gas. Some external developments that influence the demand for L gas are temperature, economic growth, efficiency improvements and development of substitutes for household heating/insulation. As this research focuses on the implications of demand profiles to the functioning of the system and the robustness of policy responses, the changes in pattern of the curves has been evaluated rather than the reasons for these changes.

7.1.1 Temperature related demand vs. temperature unrelated demand

The L gas system has to deliver both commodity (the total yearly volume of gas demand) and the production flexibility and production capacity to supply gas during peaks in demand. Policy responses need to safeguard these two system requirements. Therefore, these two components of gas demand form the basis for the demand profiles as designed in this chapter. Commodity is reflected in the part of gas demand that is independent on the weather. Peak capacity demand is reflected in the part of gas demand that is dependent on the weather. The four demand profiles in this research are designed by combining low values and high values for these two components of gas demand.

Profile 1: Low decrease in temperature related demand, low decrease in temperature unrelated demand.
Profile 2: Low decrease in temperature related demand, high decrease in temperature unrelated demand.
Profile 3: High decrease in temperature related demand, low decrease in temperature unrelated demand.
Profile 4: High decrease in temperature related demand, high decrease in temperature unrelated demand.

In Netzentwicklungsplan Gas 2012, the German TSOs have based their plans for the future development of the grid on an earlier study of the future development of gas demand. In this study, it appeared that a decrease of 3% in 2022 with respect to the demand in 2011 is the most conservative estimation for the decrease. Their most optimistic estimation is a decrease in 2022 of 19%. This research has used these estimations in the building of four demand profiles. The low decrease equals an average decrease of 0.3% per year. The high decrease equals an average decrease of 1.75% per year. This decrease is also recognized for the Dutch market, among others by (CERA and IHS 2011). As temperature dependent demand and temperature independent demand are considered as two independent parts of L gas demand, the four demand profiles are deducted from the matrix in chapter 7.1.

7.1.2 Mathematical split of both types of demand

In order to make this distinction between commodity and peak capacity, L gas demand is split into one temperature dependent part and one temperature independent part. A similar approach is applied by “Platform Versnelling Energieliberalisatie” in a flexibility analysis by CIEP (2011).

According to the KNMI (2012), the cut off temperature for L gas demand is 18 degrees (wind correlated). Above 18 degrees Celsius, the demand for L gas is no longer temperature dependent. As gas demand also has a
weekly pattern (different pattern of use for e.g. a Monday compared to a Friday), these days are also grouped by weekday, with a different temperature unrelated demand for every weekday. Mathematically:

\[ \text{Temperature Unrelated Demand on weekday } i = U_i = \frac{\sum \text{Demand}_i(T \geq 18)}{N} \]  \[ (1) \]

In this research, it is assumed that the L gas demand increases linearly if the wind correlated temperature drops under 18 degrees Celsius. This linear relation can be expressed as \( y = ax + b \) with \( x \) being the temperature. By plotting the wind correlated temperatures against actual gas demand, best-fit regression in excel has resulted in values for the parameters in the formula for temperature related demand.

\[ \text{Temperature Related Demand on weekday } i = R_i(T) = \alpha_i + \beta_i T \]

With

\( \alpha_i \): Average gas Demand at \( T (= \text{temperature}) = 0 \) on weekday \( i \)

\( \beta_i \): Average increase in L gas demand per 1 degree Celsius on weekday \( i \)

Mathematically, this gives the following formula for L gas demand:

\[ \text{Gas Demand}_i(T) = \text{MAX}(U_i, R_i(T)) = \text{MAX}(U_i \alpha_i + \beta_i T) \]

The parameters in the formulas above have been calculated separately for the Belgian L gas demand, the German L gas demand and the Dutch L gas demand. It appears that there are clear differences between the three regions. Generally, German L gas demand is for a relatively large part temperature independent, while in the Netherlands the average temperature unrelated demand is lower compared to Germany, but the sensitivity of demand to temperature is twice as high in the Netherlands compared to Germany. This difference can most likely be explained by a difference consumer portfolio: Temperature related demand is mostly the result of domestic gas demand, while a flat demand pattern generally described a larger share of industrial demand.
7.1.3 4 demand profiles

Former correlations have been used to come up with four possible demand profiles over the modeling period. In Figure 7.3, an example of the four demand profiles is plotted, according to the formula:

\[ \text{Gas Demand}_i(t) = \max(U_i R_i(t)) = \max(U_i \alpha_i + \beta_i T). \]

As can be seen, the 4 profiles cover both changes in fluctuations (variation in peak demand) as in base load (variation in commodity) and therefore form a satisfying range of demand profiles. Together, all four profiles cover different requirements to the L gas system. Policy responses are tested to all four demand profiles in order to test their robustness. The four graphs in figure 7.4 show the patterns of the four demand profiles, all relative to the low decrease in demand profile (LL). The graphs in both 7.3 and 7.4 do not represent real data and are only shown to indicate the differences between the four demand profiles.

![Figure 7.2 Indicative L gas demand as a function of temperature for the four demand profiles in this research.](image-url)
7.2 Policy responses

3 alternatives to mitigate possible problems related to the decline in Groningen production capacity have been discussed: investment in extra nitrogen capacity, investment in extra storage capacity and transition of L gas grids to H gas grids. These three alternatives are used to develop 5 possible policy responses to this decline. Transition of L gas grids into H gas grids and installing extra nitrogen capacity are the two most important responses. Extra storage capacity is considered a commercial activity and has the potential to extend the occurrence of a problem rather than to solve it and is therefore not considered in the initial policy responses in this chapter. After simulating the different scenarios, the commercial attractiveness of an investment in extra storage capacity is considered, based on the values for the parameters that are relevant to this investment decision.

The 5 policy responses used in this scenario analysis are combinations of transition of grids and the installation of extra nitrogen capacity. 5 different patterns of transition are used. It is assumed that nitrogen capacity will be installed if the demand in the scenarios is too large for the NWE L gas system to be provided.
Typically, a pattern of transition exists of the order of transition and the speed of the transition. These two parameters are used to design 5 policy responses, as reflected in the matrix in the beginning of this chapter. In the following chapters, the assumptions for every country in the policy response are discussed.

### 7.2.1 Parameters: the order of transition and the speed of transition

Three orders of transition have been defined: No transition of grids at all, just transition in gas importing countries, and transition of grids in all countries. In this chapter, the assumptions behind these orders are discussed. By choosing these three categories, it is assumed that the exports to Germany will respond in a similar way as the exports to Belgium and France.

The second parameter is the speed of the transition. It assumed that a transition follows a linear line towards a predetermined end goal. This end goal is expressed as a percentage of the amount of households connected at the beginning of the transition. As this decrease in households connected is assumed to follow a linear pattern, every year the same percentage of the amount of customers at the beginning of the transition is deducted from the total demand. As an example, figure 7.5 shows a transition starting in 2022 with an end goal of a 90% transition of grids in 2031 compared to 2022. This decrease is independent on a possible decrease in demand as discussed in the demand profiles in chapter 7.1.

![Graph showing a transition of grids](image)

**7.4 A transition of grids in which a constant decrease has been assumed**

For the Netherlands, it is assumed that there will be no transition of grids before 2022. As discussed, until 2022 GTS is legally obliged to maintain the quality of the L gas in the Dutch L gas system within its current quality specifications. As there will be no new households connected to L gas grid in the Netherlands, the Dutch demand might change before 2022 based on the demand profiles designed in chapter 7.1. After 2022, transition does occur in 2 out of 5 policy responses. If the transition of the L gas grid in the Netherlands occurs after 2022, it is most likely that this will be a controlled transition. Therefore, the speed of a transition in the Netherlands is assumed to be slow always, with an end goal of a 50% transition in 2031, implying a yearly decrease of 5.6% a year.

For Belgium and France, it assumed that the demand is not affected by the demand profiles before 2022. This, because the amount of households connected to the L gas grid is still increasing in Belgium. This increase is...
balanced out by converting some L gas grids to H gas grids. Therefore, the 'no transition' scenario for Belgium
implies a constant L gas demand until 2022. After 2022, it assumed that no more new households are
connected to the L gas grid and the demand profiles start affecting the L gas demand from that time on.

Slow transition of the Belgian grid starts after 2022 resulting in a controlled transition towards a 50% transition
in 2031. The fast transition starts in 2017 already and continues until a remaining 10% in 2031.

For Germany, it is assumed that the planned transition of grids to compensate for declining indigenous
production continues until 2022, with an annual 2.6%, which is in line with the average yearly decline of this
production, relative to its contribution to the total supply of L gas. As in these planned reductions the decrease in
L gas demand per customer is already taken into account, the different demand profiles do not start to affect the
German demand until 2022. After 2022, the slow transition implies a transition of 50% until 2031, while the fast
transition implies a transition of 90% of all customers in 2031, implying an annual transition of 10% of the
demand in 2022.

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>Belgium and France</th>
<th>The Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>slow</td>
<td>start</td>
<td>2022</td>
<td>2022</td>
</tr>
<tr>
<td></td>
<td>end goal (2031)</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>decrease per year</td>
<td>5,60%</td>
<td>5,60%</td>
</tr>
<tr>
<td>fast</td>
<td>start</td>
<td>2022</td>
<td>2017</td>
</tr>
<tr>
<td></td>
<td>end goal (2031)</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>decrease per year</td>
<td>10%</td>
<td>6,40%</td>
</tr>
</tbody>
</table>

Table 7.1 The numerical assumptions for the speed of transition as used in the 5 policy responses

7.2.2 Extra nitrogen capacity

In the design of the four policy responses, it is assumed that the L gas demand that cannot be provided for by
the L gas system, is to be provided by building extra nitrogen capacity. This is implemented in the simulation by
adding an extra source of nitrogen at the two central blending stations of Wieringermeer and Ommen. The costs
of nitrogen production at these extra facilities are modeled to be very high, and therefore it will only be used
when there is no other source available within the system. Monitoring the usage of these extra nitrogen facilities
during the simulation time reveals the pattern of use of these extra nitrogen production facilities and the way that
this usage differs between the different scenarios. These patterns of use are translated into investment needs in
every scenario.
Phase 1 Background: General functioning L gas system

Input
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH3)

Output
1. Concepts and definitions natural gas systems (CH2)
2. Basic understanding L gas system (CH2)
3. Main stakeholders and interests regarding gas quality (CH3)

Phase 2 Modeling

Input
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach these objectives? (CH3)
3. How is this general modeling technique applied to the WIE L gas system? (CH4.5)

Output
1. General modeling approach (CH3)
2. Main system constraints (CH3.4)
3. L gas system components and capacities (CH.4)

Phase 3 Stakeholder behavior analysis

Input
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementations? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPIs in the L gas system and how would stakeholders respond to changing KPIs? (CH6)

Output
1. Technical alternatives (CH6)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

Phase 4 Integrated scenario analysis and conclusions

Input
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPIs evolve in the different scenarios and how are stakeholders expected to respond? (CH6.9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH6.9)
4. To what extent did the chosen modeling technique approach meet initial requirements? (CH10)

Output
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH9)
4. Recommendations to Dutch government and EBN (CH11)
5. Reflection on modeling approach (CH10)
8 Scenario Analysis

The 20 scenarios designed are run in the simulation tool as developed in this research. This chapter elaborates on the outcomes of these runs. In chapter 8.1, a recap is given of the main modeling steps and the important variables to consider are recaptured from chapter 6. These variables are derived from the problem statement, the modeling objectives and the analysis of alternatives, the latter being the major contributor as the diverging stakeholder preferences and decision criteria are analyzed there. From chapter 8.2 on, these variables are tested per policy response. The policy responses are tested on their robustness to different demand profiles. The findings of the separate policy responses are integrated in chapter 9, in which general findings are summarized into conclusions on the L gas system in North West Europe.

This chapter integrates the quantitative modeling part of this research with the qualitative analysis of stakeholder behavior. It aims to answer the following research questions:

1. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond?
2. How is the physical balance between supply and demand expected to evolve in these scenarios?

The results presented in this chapter are the results of running the simulation tool under the assumptions in this research. As discussed in chapter 3 and 4, these outcomes must be seen in the perspective of these assumptions. Chapter 10 discusses the consequences of these modeling assumptions to the model outcomes and it gives recommendations of how this could have been overcome.

8.1 Recap of main research components

In order to understand and interpret the results presented in this chapter correctly, a brief recap of the main research components is presented. Chapter 3 has defined the modeling approach as: “Optimization of utilization of supply sources according to a merit order, to supply demand within the technical constraints of the system”. This comprises two main factors: the merit order of supply sources and the choice for technical system constraints. Chapter 6 has listed the preferences off all stakeholders regarding the scenarios and transformed these into KPI for the system. Chapter 7 has designed 20 scenarios.

8.1.1 Merit order of supply sources

The merit order of supply sources, being the prioritization of supply sources under the assumption that one source is used optimally until production is constrained by one of the main system constraints, as been set at:

1. L gas production of Small fields (sometimes off spec H gas) and German production
2. L gas production in Groningen
3. L gas in UGS
4. H gas blending (until upper Wobbe range)
5. H gas + nitrogen

6. (Non-existing Nitrogen capacity + H gas)

8.1.2 System constraints
The 5 main system constraints used in the simulation tool are:

1. Demand constraints
2. Production constraints
3. Storage constraints
4. Quality constraints
5. The existence of physical connections

System constraints that have been chosen to be outside the scope of this research are, among others:

- Unlimited supply of H gas is assumed
- Pipeline capacity is not integrated in the model but only evaluated at some critical points

8.1.3 Performance Indicators for the L gas system
Chapter 6 concluded with the main performance indicators for the L gas system. In this chapter, these indicators are recaptured briefly as the following chapters will address the questions regarding these parameters.

*Nitrogen Usage*

1. Extra nitrogen capacity:
   a. When?
   b. How much?
   c. What model?
   d. Location?

2. Current nitrogen capacity
   a. Patterns of use

*Production pattern of Groningen production*

For all scenarios, the Groningen sales targets for GasTerra are evaluated and the implication of the production pattern is discussed.
Use of H gas for blending

1. What peak H gas capacity is needed to balance supply and demand?
2. How does this compare to other scenarios?
3. What is the demand for flexibility of H gas delivery?
4. How does the market share of L gas evolve?

Utility of Storage facilities and options for investment

1. Commercial attractive to invest in new UGS?
2. What happens to existing storages?

8.1.4 5 policy responses against 4 demand profiles

To recap from the preceding chapter, the demand profiles are named in abbreviations. The first letter of the abbreviation reflects the magnitude of decrease of the temperature dependent part. The second letter of the abbreviation reflects the magnitude of the temperature independent part. ‘L’ stands for Low decrease; ‘H’ stands for High decrease. See figure 8.1.

<table>
<thead>
<tr>
<th>Transition of grids</th>
<th>No transition</th>
<th>Foreign grids</th>
<th>All grids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of transition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>PR 1</td>
<td>PR 2</td>
<td>PR 4</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td>PR 3</td>
<td>PR 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decrease in T related</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease in T unrelated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>LL</td>
<td>HL</td>
</tr>
<tr>
<td>High</td>
<td>LH</td>
<td>HH</td>
</tr>
</tbody>
</table>

Figure 8.1 Five Policy Responses from the left Matrix are combined with 4 Demand Profiles from the left matrix to get 20 future scenarios

8.2 Policy Response 1: no transition

8.2.1 Nitrogen usage

The first policy response implies that there will be no transition of grids at all, except for the planned transition in Germany in order to compensate for the decline in domestic production. In this scenario, the gradual decline in Groningen production capacity is firstly mitigated by existing nitrogen capacity, as can be seen in Figure 8.2. This graph confirms the general trend in the current L gas system. From winter 2013 on, the use of nitrogen in the system increases. Because of the nitrogen overcapacity in the current situation the system is flexible enough to mitigate the decline in Groningen production in the first years.
Figure 8.2 plots the utilization of non-existing nitrogen production facilities. In this graph, some interesting things can be seen. Firstly, the nitrogen production seems to have three peak years between 2017 and 2020. In this period, the peaks are mainly in winters. In the winter, the gas demand will be relatively high, so nitrogen appears to be used to deliver peak capacity. After 2020, the nitrogen production decreases steeply, where after it starts to increase again.

In many of the graphs as delivered from the simulation tool, a pattern can be seen that has two different types of behavior per year. In the winter, the graphs follow a comparable pattern, and in the summer as well. The most logic reason for this would be the cold weather with peak demand in the winter, and the warm weather and storage injection in the summer. However, the time span as chosen in this research also follows this pattern, and the simulation tool optimizes stepwise per this same period. Thus, these patterns could also have been the result of this modeling choice. This overlap makes it difficult to verify the model in these graphs. This should always be kept in mind if surprising results would come out of the model output.
Figure 8.3 Production in non-existing nitrogen production facilities in Policy response 1.

If there is no transition of grids in the North West European L gas system at all, first problems are expected to arise around 2025 as can be seen in figure 8.3. At that time, present nitrogen capacity is not expected to be sufficient in all demand profiles, and extra nitrogen capacity is necessary in order provide for the demand.

After 2025, the need for extra nitrogen production capacity increases yearly, with a peak demand of 17,76 mcm/day (see figure 8.3 and 8.4). This is equal to 750,000 cubic meters per hour, 1.5 times the total installed capacity in 2011. Interesting in figure 8.3 is that in the first years of operation, extra nitrogen is mainly used in the summer. In the winter, the need for extra nitrogen becomes apparent later, from 2028 on. Apparently, the L gas provision in summer is no longer sufficient to provide for the demand and to fill the storages to full capacity before the winter comes in at the same time. In this scenario, the very expensive new nitrogen facilities are built to fill these storages. This is the consequence of the modeling assumption that all storages are filled to their maximum at the beginning of the winter period. The consequences of this modeling assumption are discussed more extensively in chapter 10.3, in which a reflection on all main modeling assumptions is presented.

Eventually, the extra nitrogen capacity is used throughout almost the entire year (see figure 8.3). So, the modeling assumption that all storages are filled before the winter comes in has put the need for an investment forward in time. The peak, however, appears in the winter, January 2030. So, this assumption did not impact the magnitude of this investment.
Another modeling choice that does have a role in the height of this peak is the costs assigned to the new nitrogen production. By assigning the same costs to all nitrogen produced in new nitrogen production locations, the model does not differentiate between the timing of this production. However, it is clear that it is cheaper to produce with one new facility at full capacity for one week than to produce the same amount of nitrogen with 7 new facilities at only one day.

This assumption might influence the peak demand of new nitrogen facilities, but not the total amount of nitrogen produced. Also, the date of a peak could show whether a different modeling approach would have flattened this peak. A peak in summer to fill storages can most likely be allocated more equally, as the filling of a storage is not that time dependent. A peak in winter however is less likely to be flattened by a different modeling approach. Also, when the Groningen production cap is still applicable, the optimization process might ask for a peak demand to safe Groningen for later in the optimization. If the Groningen cap is no longer applicable, all supply sources will be producing at full capacity already, so there is no room for using a peak demand of new nitrogen in order to safe production capacity in the near future. In this specific case, the peak demand appears in a winter and after the production cap, so the effect of this assumption on this peak is expected to be limited. Again, the consequences of this modeling assumption is discussed more extensively in chapter 10.3.

8.2.2 Conversion costs

Because there has been no start with the transition of grids, it can be assumed that this demand for extra nitrogen capacity will last for the years after 2031. Based on this, the model in which GTS builds and operates the facility would be favorable in this scenario. The costs in this scenario are to a large extend the investment costs for the to-be-build extra nitrogen production facilities.
Next to the investment costs, the operational costs of nitrogen production will grow significantly in this scenario. In chapter 6, these costs have been estimated to be €0.05 per cubic meter nitrogen. With this assumed price, the yearly costs of nitrogen production are plotted in figure 8.5.

This implies risks for maintaining the socialization of conversion costs. As discussed earlier, if the conversion costs are no longer socialized, the quality label will have to be brought back at the TTF, thereby reducing the liquidity of the TTF drastically as its churn rate will decrease. The liquidity of the TTF is considered to be an important feature for the Dutch position in the European gas market. Therefore, the quality at the TTF is to be maintained unlabeled if the TTF has to be a leading gas hub in Europe.

8.2.3 Groningen Production

In figure 8.6, the production in Groningen is plotted.

Groningen produces with a fluctuating pattern. It has an important role in providing for the flexibility within the system, as can be seen in the difference between peak capacity and base load. This results in time periods at which Groningen cannot produce despite of its available capacity. In the summer, demand is lower but there is additional demand from the storages. In this time of the year, the beginning of October, all storages will be filled but the demand is still not high enough to let Groningen produce at its maximum.

8.2.3 Use of H gas for blending and UGS

In this scenario the amount of H gas for blending grows significantly in the coming years, with a peak of 250 mcm/day in 2029, as can be seen in figure 8.9. Also, the flexibility of H gas blending increases drastically. Comparing the graph with the Groningen production and the graph with H gas blending, it appears that H gas + nitrogen is taking over the role of the Groningen field as the main supplier of flexibility.
As H gas production flexibility is generally low because of the high capital costs of long distance transportation infrastructures, the market for this flexibility might get interesting, as the swing function of the Groningen field will be disappeared after 2020. It might be commercially attractive to fill this gap with a H gas storage close to a nitrogen production facility.

![H gas blended in the L gas grid](image)

In figure 8.9, it can be seen that H gas blending initially only takes place in the winter, when the peak demand cannot be provided with the original L gas supply sources. From 2020 on, H gas blending becomes more and more used throughout the entire year. That means that from this date, the L gas in the storages is partly H gas blended with nitrogen.

Something else that is interesting in this graph 8.9 is that the difference between the 4 demand profiles becomes more and more apparent; in the beginning the profiles are hardly distinguished from each others, but in the end the demand for H gas in the LL profile is significantly larger than the HH profile.

Based on the production pattern of Groningen in figure 8.8 en table 8.1, extra storage of L gas does not seem to be attractive in this scenario. Groningen is already producing at its maximum and therefore L gas storage does not seem to be attractive, as increasing L gas storage would have the main objective to increase production in Groningen.

### 8.2.4 Conclusions

In the analysis of policy response 1, many interesting results have become apparent. Not only results from the L gas system and its development until 2030 in policy response 1, but also about the working of the simulation tool and the bias that certain assumptions have had on the results. Most of these results will show itself in the other policy responses, too. In these policy responses, they will not be discussed as extensively as for this policy response. Therefore, the main things are listed to get a better overview of these results. When assessing the results from the other policy responses, these should be kept in mind. In the reflection on the modeling tool in chapter 9 and in chapter 10, these assumptions will be discussed on their implications and their consequences.
for the modeling accurateness. The following influences of the model on the modeling outcomes have been identified:

- Constant price for new nitrogen facilities might lead to too high peaks in nitrogen demand

- The production cap has not been modeled satisfactorily, leading to unrealistic Groningen patterns until 2020

- The situation in which new nitrogen facilities are built to fill storages in summer could be evoked by the assumption of full storages at the beginning of the winter
8.3 Policy Response 2: slow transition in Belgium, France and Germany

8.3.1 Nitrogen usage
In policy response 2, a slow transition is started from 2022 on. Regarding the use of existing nitrogen facilities, one can see a comparable pattern as in policy response 1 (see figure 8.10), but the pattern has shifted from a relatively flat utilization to peak demand. In the first 5-10 years, nitrogen demand is mainly in the winter time. Later in the simulation time, nitrogen has also been used in summer time, to fill the storages with H gas diluted with nitrogen. One can question the durability of this situation in which it seems that the total L gas supply is insufficient for the demand. This question will be discussed in the conclusions and recommendations part.

Figure 8.8 utilization of existing nitrogen facilities

Figure 8.11 shows that starting a slow transition in Belgium, France and Germany from 2022 on has not taken away the need for extra nitrogen production facilities. Especially in the beginning, this production pattern is very fluctuating instead of constant. With the large start-up time and start-up costs of a nitrogen production facility in mind, this pattern of use seems most suitable for a relatively small production location and a nitrogen storage with a high withdrawal rate, as in Heiligerlee. For this scenario, all extra nitrogen demand is in the summer, as discussed before this is to fill the storages. It could be explored whether changing some L gas storages into H gas storages might flatten this pattern.
8.3.2 Conversion costs

Again, the existing nitrogen facilities are being used more often as compared to previous years, leading to an increase in conversion costs. From 2013 on their utility will grow yearly.

Next to the investment in extra conversion capacity, the policy response of a transition of networks implies investments. These costs are carried by the TSOs in the countries in which this transition takes place. These costs are outside the scope of this research.

8.3.3 Groningen production

The Groningen production pattern follows a comparable pattern as was seen in policy response 1.
Based on this Groningen production, a small transition of grids in gas exporting countries does not seem to affect the optimal utilization of the Groningen field, which was identified as one of the main public values that the Dutch government has to safeguard. Also, the different demand scenario’s do not seem to have a large effect on the income from the fields; the difference in NPV is relatively small. However, between the low decrease in demand and the high decrease in demand, there is still a difference of €150 million in NPV. This is higher than the NPV of the investment costs in new nitrogen capacity.

<table>
<thead>
<tr>
<th></th>
<th>LL</th>
<th>LH</th>
<th>HL</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total production (bcm)</td>
<td>779,61</td>
<td>779,14</td>
<td>779,44</td>
<td>778,92</td>
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<tr>
<td>average yearly production (bcm)</td>
<td>39,98</td>
<td>39,95</td>
<td>39,97</td>
<td>39,94</td>
</tr>
<tr>
<td>Production until 2020</td>
<td>437,84</td>
<td>437,78</td>
<td>437,79</td>
<td>437,73</td>
</tr>
<tr>
<td>NPV with a vast price of €0,25/m³, discount rate of 3% (bln €)</td>
<td>152,21</td>
<td>152,10</td>
<td>152,15</td>
<td>152,07</td>
</tr>
</tbody>
</table>

### 8.3.4 Use of H gas for blending and UGS

From figure 8.15, it becomes clear that the role of H gas will change in policy response 2 too. Compared to Policy Response 1, the peak capacity for H gas blending has decreased significantly to 160 mcm/day peak. To put this amount of flexibility into perspective, the peak capacity of the UGS in Norg after the extension in 2017 is in the region of 96mcm/day. Existing sources of flexibility for H gas could partly fulfill this demand.
Figure 8.13

H cal gas blended into the L gas grid
8.4 Policy Response 3: fast transition in Belgium, France and Germany

This simulation entails the scenario in which the exporting countries start their transition quickly and drastically. In 2031, only 10% of the customers connected to the L cal grid in these countries are still connected to L gas; the other customers have either been converted to the H cal grid or have been connected to other energy sources.

8.4.1 Nitrogen usage

![Chart showing Utilization of existing Nitrogen capacity in HL](chart.png)

When this scenario is followed, extra nitrogen capacity will be necessary in the winter of 2029. This is one large peak of 5,31 mcm/day (see figure 8.17). The demand for this extra capacity is lowered again in the next winter, based on which one can expect that this demand will decrease even further after 2031. Therefore, this extra capacity, with an estimated investment of €100 million, would only have to be installed for a short period of time. It would not make sense to do this large investment for this short time period. An industrial partner that takes over the plant after these years, or that uses the plant for other air separation processes needs to be found to make this extra capacity economically feasible.

Recapturing on the influence of the assumptions regarding the costs of extra nitrogen capacity, it can be expected that this peak can be flattened, and that only one extra nitrogen facility will have to be build. As explained, the simulation tool does not differentiate between one high peak and several smaller peaks. However, it can be concluded that the current installed nitrogen capacity is not sufficient in this scenario.
8.4.2 Conversion costs

Existing nitrogen production capacity is used increasingly and with a flat pattern until 2026, after this the utilization is limited to incidental peaks. It is expected that existing nitrogen production facilities will decrease further after 2031. In this scenario, it appears that the conversion costs will be significant, especially in the period from 2020 until 2026. However, compared to the earlier scenarios, the increase is expected to be controllable: In the LL demand profile the conversion fee is expected to have been doubled compared to the current conversion fee. The negative consequences and the risks for high conversion costs regarding among others the liquidity of the TTF have been discussed before.

8.4.3 Groningen production

The Groningen production in this scenario follows a comparable pattern as in the preceding policy responses. The HL run of this scenario had experienced an error with the storages in 2015. This is the reason for the relatively low values for this demand profile in table 8.3. During this research this error was not fixed in time and therefore these values have not been taken into account in this research.
### Table 8.1 Groningen production numbers in policy response 3 per demand profile

<table>
<thead>
<tr>
<th></th>
<th>LL</th>
<th>LH</th>
<th>(HL)</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total production (bcm)</td>
<td>779,05</td>
<td>778,41</td>
<td>(764,73)</td>
<td>777,67</td>
</tr>
<tr>
<td>Average yearly production (bcm)</td>
<td>39,95</td>
<td>39,92</td>
<td>(39,21)</td>
<td>39,88</td>
</tr>
<tr>
<td>Production until 2020</td>
<td>445,68</td>
<td>445,62</td>
<td>(431,60)</td>
<td>445,36</td>
</tr>
<tr>
<td>NPV with a vast price of €0,25/m³, discount rate of 3% (bln €)</td>
<td>152,09</td>
<td>151,98</td>
<td>(148,94)</td>
<td>151,88</td>
</tr>
</tbody>
</table>

8.4.4 Use of H gas for blending and UGS

Figure 8.17

With respect to the H gas blending capacity, once can see that the increase in utilization of nitrogen from 2013 on affects the peak capacity for H gas blending. This increase in capacity is controllable and does not increase after 2018. Therefore it seems that investment in extra storage capacity is not attractive in this policy response, as this storage will not be operational before 2018 if an investment decision would be made now. However, as H gas capacity has been outside the scope of this research, the expectation that this demand pattern for H gas can be delivered within the current H gas system needs to be checked.
8.5 Policy Response 4: slow transition of all grids

In this scenario, not only the grids in L gas importing countries are converted, but also within the Netherlands a slow and controlled transition starts in 2022. From a Dutch point of view, this would reduce the dependency of a quick transition in foreign countries and the balancing problems that might arise if these transitions do not go as planned.

8.5.1 Nitrogen usage

![Utilization of existing nitrogen capacity (HL)](image)

With a slow transition of all grids, current installed nitrogen capacity is not sufficient to provide demand in the winter of 2028 as can be seen in figure 8.21. The peak demand for extra nitrogen capacity would then occur in the winter of 2029, with a peak of 7.88 mcm/day. This would require an estimated investment of €150 million.
As can be seen in figure 8.21, the peak is high but relatively short, as the demand for extra nitrogen capacity already decreases after 2029. Therefore, it does not seem to be economically viable to build a new facility. Contracting nitrogen production capacity seems to be the most appropriate way to provide for this demand.

8.5.2 Conversion costs

The utilization of current installed nitrogen capacity is high on peak demand, but the peaks are relatively short and therefore a large increase in conversion costs is not to be expected in comparison to this cost increase for other policy responses. This is reflected in the operational costs of nitrogen facilities in figure 8.22.

However, these costs for nitrogen production are not all the costs for the Dutch government. The costs of the transition in the Netherlands are high; Based on the KEMA/KIWA report "Gaskwaliteit voor de toekomst" (2011) these costs would be in the region of €500 – 1000 million. When using the estimated costs of €150 per household and assuming 8 million households in the Netherlands in total, a 50% transition would cost €600
million. Next to this, additional investments in infrastructure capacity are expected to be necessary to provide this transition.

It can be questioned whether this large investment in a conversion of grids is favorable above extra investment in nitrogen capacity as described in the policy response before. In order to make this consideration, the total costs are to be compared between different policy responses. Also, the societal impact of these policy responses should be taken into account; as described in chapter 6, a large scale transition of L gas grids to H gas might have large impact on society and the reputation of natural gas as a reliable and safe source of energy. Nitrogen production is a proven concept for which the roles are clear and the distribution of costs has been set. This should be taken into account when comparing policy responses.

8.5.3 Groningen production

Groningen production patterns follow a similar pattern, again, as can be seen in table 8.4. Even with the relatively low gas demand in these scenarios, GasTerra’s production targets for the Groningen field are still met.

<table>
<thead>
<tr>
<th></th>
<th>LL</th>
<th>LH</th>
<th>HL</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total production (bcm)</td>
<td>779,36</td>
<td>778,74</td>
<td>779,09</td>
<td>777,94</td>
</tr>
<tr>
<td>average yearly production (bcm)</td>
<td>39,96</td>
<td>39,93</td>
<td>39,95</td>
<td>39,89</td>
</tr>
<tr>
<td>Production until 2020 (bcm)</td>
<td>445,72</td>
<td>445,66</td>
<td>445,68</td>
<td>445,61</td>
</tr>
<tr>
<td>NPV with a vast price of €0,25, discount rate of 3% (bln €)</td>
<td>152,17</td>
<td>152,04</td>
<td>152,09</td>
<td>151,92</td>
</tr>
</tbody>
</table>

Table 8.2 Groningen production numbers in Policy response 4 per demand profile

8.5.4 Use of H gas for blending and UGS

H gas blending capacity follows a more or less stable pattern over the years, which is only slightly disturbed by the end of the production cap in 2020. The H gas demand peaks at about 140 mcm/day, which is not significantly different compared to the former policy response. Especially in the period 2018-2020 the demanded peak capacity is high for a longer period of time, requiring a large working volume for H gas. In the period 2020-2030 peak demand mainly occurs in short term peaks, for which usually a depleted salt cavern is the most appropriate type of storage to install.
8.6 Policy response 5: fast transition of all grids

8.6.1 Nitrogen usage

In the final policy response, all grids are converted with the quick schedule, except for the Dutch grid, that starts a transition in 2022 with a moderate speed, resulting in a 50% transition by 2031. By implementing this order and speed of transition, there is no need to invest in extra nitrogen production capacity in any of the four demand profiles as can be seen in figure 8.25. Also, the utilization of existing nitrogen capacities is controllable; the utilization increases but this utilization is mainly in peak demand (see figure 8.24). A situation in which nitrogen is produced flat throughout the year as seen in other scenarios does not occur in these scenarios.
8.6.2 Conversion costs

Also the conversion costs are controllable in this scenario, as can be expected. In the years until 2018, however, the conversion fee will increase, even in this scenario, see figure 8.27.
In this scenario, the investments needed are limited to the investment for the transition as elaborated on for policy response 4, in the region of €600 million plus investments in infrastructure.

8.6.3 Groningen production

This does not lead to a significant lower production of Groningen gas, as can be seen in table 8.4 in which the production parameters of the two extreme policy responses, no transition and fast transition, are compared. Only in a combination of the high decrease demand profiles shows significant differences in the NPV. In combination with the HH demand profile, this difference in NPV is €1,5 billion, which is a large amount of money, but relatively low as it compares two extremes. However, both scenarios also involve different costs in extra nitrogen capacity at the one side, and the costs of a transition of grids at the other. These costs should be compared in order to come up with a solid comparison of the policy responses.

<table>
<thead>
<tr>
<th></th>
<th>LL PR1</th>
<th>LL PR5</th>
<th>LH PR1</th>
<th>LH PR5</th>
<th>HL PR1</th>
<th>HL PR5</th>
<th>HH PR1</th>
<th>HH PR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total production (bcm)</strong></td>
<td>779.77</td>
<td>778.86</td>
<td>776.21</td>
<td>776.21</td>
<td>779.63</td>
<td>775.64</td>
<td>779.26</td>
<td>770.57</td>
</tr>
<tr>
<td><strong>NPV with a vast price of €0.25/m$^3$ discount rate of 3% (billion €)</strong></td>
<td>152.23</td>
<td>151.91</td>
<td>152.19</td>
<td>151.66</td>
<td>152.18</td>
<td>151.58</td>
<td>152.13</td>
<td>150.85</td>
</tr>
</tbody>
</table>

Table 8.3 Groningen production numbers compared between the two extreme policy responses.

8.6.4 Use of H gas for blending and UGS

In this policy response, H gas peak capacity demand increases.
Demand pattern for H gas blended in the L gas system in policy response 5

Figure 8.25
**Phase 1** Background: General functioning L gas system

**Input**
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH3)

**Output**
1. Concepts and definitions natural gas systems (CH2)
2. Basic understanding L gas system (CH2)
3. Main stakeholders and interests regarding gas quality (CH3)

**Phase 2** Modeling

**Input**
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach these objectives? (CH3)
3. How is this general modeling technique applied to the NWE L gas system? (CH4,5)

**Output**
1. General modeling approach (CH3)
2. Model order of supply sources (CH3)
3. Main system constraints (CH3,4)
4. L gas system components and capacities (CH4)

**Phase 3** Stakeholder behavior analysis

**Input**
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH6)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPIs in the L gas system and how would stakeholders respond to changing KPIs? (CH3)

**Output**
1. Technical alternatives (CH6)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

**Phase 4** Integrated scenario analysis and conclusions

**Input**
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond? (CH6,9)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH6,8)
4. To what extend did the chosen modeling technique approach meet initial requirements? (CH10)

**Output**
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH9)
4. Recommendations to Dutch government and EBN (CH11)
5. Reflection on modelling approach (CH10)
9 Integrated results of scenario analysis

Chapter 8 has evaluated the key performance indicators of the L gas system in NWE per policy response. In this chapter these results are compared and integrated into the larger multi stakeholder arena in which the decision making takes place. This chapter aims to answer the following research questions:

1. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond?
2. How is the physical balance between supply and demand expected to evolve in these scenarios?

This chapter starts in chapter 9.1 by analyzing the Dutch government’s objectives in the different policy responses, and it explores too what extend the different policy responses safeguard the public values that the Dutch government has within the L gas system. After this analysis from the perspective of the Dutch government, chapter 9.2 evaluates the KPI and all stakeholder preferences towards these KPI.

9.1 Public values for the Dutch government

In chapter 1, the problem of the decline in L gas production capacity to the Dutch government has been defined as a potential threat to two important values within a natural gas system: the optimal utilization of natural resources and a reliable supply of gas, both in terms of security of supply as in safety.

9.1.1 Reliable supply of gas

One of the conclusions from the stakeholder analysis in chapter 6 is that the system is organized in such a way that an imbalance between supply and demand is unlikely to appear. GTS has the legal role to provide for sufficient conversion capacity and therefore this conversion capacity has been used to balance supply and demand in all scenarios.

However, there are different alternatives to maintain this balance and these alternatives impact the reliable gas supply in different ways. A transition of L gas grids to H gas grids has the largest impact on society. Consumers are put to large and inevitable costs, for example for replacing their central heating system. The costs and the need for coordination of this alternative are high, as are the safety hazards. Therefore, this alternative could potentially harm this value and therefore, for the Dutch government this alternative is to be considered only when other alternatives appear to be undesirable as well. Considering the reliability of gas supply, increasing nitrogen production capacity is preferred above transition of grids.

9.1.2 Optimal utilization of natural resources

In order to utilize the natural resources optimally, e.g. in order to maximize the income from the Groningen field, the investment costs for each policy alternative are compared. Table 9.1 shows the results for each of the 5
policy responses. The total NPV of Groningen and nitrogen production are combined into one total NPV. It should be noted that especially the costs for nitrogen production are based on very rough estimates. Therefore, this table should only be used as means to compare between the different policy responses.

<table>
<thead>
<tr>
<th>Policy response</th>
<th>NPV Groningen (bln €)</th>
<th>NPV nitrogen capex (mln €)</th>
<th>NPV nitrogen opex (mln €)</th>
<th>Total NPV (bln €)</th>
<th>Costs of transition grids (mln €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>152,18</td>
<td>195,85</td>
<td>863,77</td>
<td>151,12</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>152,13</td>
<td>107,65</td>
<td>742,87</td>
<td>151,28</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>151,98</td>
<td>52,02</td>
<td>579,92</td>
<td>151,35</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>152,06</td>
<td>77,46</td>
<td>535,64</td>
<td>151,45</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>151,5</td>
<td>0</td>
<td>431,27</td>
<td>151,07</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 9.1: All investments per Policy Response

The costs of a transition of grids are not added to the total NPV, as it is expected that in every scenario these costs need to be made at some point in time. For the first 3 policy responses, this moment lies beyond the modeling scope of 20 years. For a better comparison, these costs are not included in the NPV but mentioned as distinct costs.

It appears that the alternatives in which a transition of grids is considered are not only least attractive in terms of societal impact, but financially as well. Especially in combination with a fast transition in Germany and Belgium, a process on which the Dutch government only has limited influence, the state income from the Groningen field will be significantly lower, even if the Dutch government would take all the involved costs of nitrogen production in the other scenarios.

When a transition of grids in the Netherlands is postponed until after 2030, the total income to the Dutch government will be quite comparable in all scenarios. From these three policy responses, a transition in Germany, Belgium and France from 2022 on would be most favorable according to these calculations as this would limit the extra nitrogen production capacity that need to be installed. A transition in these countries would not affect the sales from Groningen according to this research, because it will initially start reducing the production at the bottom of the merit order of supply sources as assumed in this research.

However, a natural gas system is not a central planned system as it might have been before and therefore the Dutch government cannot just decide on their most attractive option. Chapter 6 has discussed extensively how the different stakeholders within the system tend to different alternatives, and how this interaction influences the direction in which the L gas system would evolve. This chapter 6 has concluded with a number of Key Performance Indicators that are valued by the stakeholders within the system. The following paragraphs explore in what way the KPI are expected to evolve and what this does to stakeholder preferences.
9.2 Key Performance Indicators

Figure 9.1 presents the scores of the 5 policy response to the Key Performance Indicators of the L gas system as defined in this research. Based on this, we could draw general conclusions about the future of the L gas system and the robustness of the different Policy Responses as simulated in this research.

One general remark applies to all outcomes of the model. As stressed throughout this entire report, the simulation tool simulates a system that is operated optimally. Also, the daily time step has flattened the within day fluctuations. Peak hours are compensated for by hours of lower demand. This has also flattened the extremes in the modeling outcomes. Thirdly, the outcomes of the model are to a large extend dependent on the modeling assumptions that form the basis for the model. The consequences of these three remarks are elaborated on more extensively in chapter 10.3, but are important to be kept in mind while reading this chapter.

<table>
<thead>
<tr>
<th></th>
<th>PR 1</th>
<th>PR 2</th>
<th>PR 3</th>
<th>PR 4</th>
<th>PR 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak extra nitrogen demand (mcm/day)</td>
<td>17,76</td>
<td>9,87</td>
<td>5,31</td>
<td>7,88</td>
<td>0</td>
</tr>
<tr>
<td>First year of extra nitrogen used</td>
<td>2025</td>
<td>2026</td>
<td>2029</td>
<td>2028</td>
<td>-</td>
</tr>
<tr>
<td>Needed investment in new nitrogen capacity (mln €)</td>
<td>300</td>
<td>170</td>
<td>90</td>
<td>130</td>
<td>0</td>
</tr>
<tr>
<td>NPV investment nitrogen (mln €) (discount rate 3%)</td>
<td>195,85</td>
<td>107,65</td>
<td>52,02</td>
<td>77,46</td>
<td>0,00</td>
</tr>
<tr>
<td>Accumulative nitrogen used 2011 – 2030 (bcm)</td>
<td>26,09</td>
<td>22,17</td>
<td>16,92</td>
<td>15,28</td>
<td>11,91</td>
</tr>
<tr>
<td>NPV nitrogen production (mln €) (discount rate 3%; €0,05/m³)</td>
<td>863,77</td>
<td>742,87</td>
<td>579,92</td>
<td>535,64</td>
<td>431,27</td>
</tr>
<tr>
<td>H gas peak (mcm/day)</td>
<td>250</td>
<td>160</td>
<td>125</td>
<td>140</td>
<td>125</td>
</tr>
<tr>
<td>Accumulative prod Groningen (bcm)</td>
<td>778,72</td>
<td>779,28</td>
<td>778,38**</td>
<td>778,78</td>
<td>775,07</td>
</tr>
<tr>
<td>NPV Groningen production (bln €)</td>
<td>152,18</td>
<td>152,13</td>
<td>151,98*</td>
<td>152,06</td>
<td>151,5</td>
</tr>
<tr>
<td>Model for extra nitrogen demand</td>
<td>Build &amp; Operate</td>
<td>Storage Capacity</td>
<td>Capacity</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Costs for conversion of Dutch grids (mln €)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

Figure 9.1 The main results summarized for every policy response

\[5^*\] In the averages, the HL scenario in PR 3 has not been taken into account, as the values for this scenario show unrealistic values for 2015 Groningen production, making this run unusable.
9.2.1 Groningen Production

Based on the assumptions made in this research and based on the capacity constraints of the system, Groningen gas sales don't differ too much between the different scenarios. It appears that if the system would be optimally used, Groningen gas would always be producing at its maximum production capacity. Based on the assumptions of this model, the difference between the NPV of a quick transition and no transition is €700 million.

Therefore, it can be stated that the occurrence of non optimal Groningen sales are either caused by constraints that are not included into this modeling approach, for example transportation constraints, or by non-optimal use of the system. The objective of maximizing Groningen production by GasTerra seems to be in line with the objective of GTS to run the system optimally. Therefore, transparency on this between GasTerra and GTS would potentially benefit both parties.

9.2.2 Nitrogen Capacity

Except for in the most extreme transition pattern, there is always a need for extra nitrogen capacity. This extra nitrogen capacity is not needed before 2025. Therefore, there is no urgency for this investment decisions to be made on the short term. In the most extreme scenario in terms of nitrogen investment, the total demand for extra nitrogen is 150% of the current installed capacity.

Also, if there only would be a slow transition in the gas importing countries, the extra investment in extra nitrogen production capacity would be significant. As these countries are not expected to invest in their nitrogen capacity, this extra capacity will have to be built within the Netherlands.

Based on this, it can be stated that either a fast transition in exporting countries or a start of a transition within the Netherlands in 2022 is necessary in order to control the costs of this extra nitrogen capacity, if this is to be pursued. Based on the current situation as described in chapter 6, these two responses towards a conversion of grids are not expected if no further measures would be taken. In Germany, Belgium and France, the TSOs are not preparing for this fast transition.

9.2.3 Conversion costs

Nitrogen producers can expect their utilization to rise from 2013 on. The conversion costs are important to be managed, also because the non quality labeled trade of gas is an important factor for a liquid TTF.

Research conducted by De Wit (2006) for Linde Gas, which is the producer of Nitrogen in Ijmuiden, concludes that nitrogen producers do not play a role within the gas market. However, nitrogen producers are ‘the last in line’ to supply gas according to the merit order of sources as assumed in this research. Therefore these producers are the first ones that will experience a reduction in their sales if there is a transition of grids. This industry would benefit from postponing the transition.
9.2.4 H gas blending capacity

One of the main conclusions in this research is that H gas becomes more and more important for the L gas system, whether it is in the form of a threat of transition of grids or as a means to maintain the balance between demand and supply in this system. Groningen production used to be the main supplier of flexibility within the L gas system.

But as can be seen in the different H gas patterns as presented in the preceding chapter, H gas production will have to deliver flexibility too. The market for flexibility services becomes more and more attractive as the Groningen field leaves a commercially interesting gap. In this research the production capacity and flexibility of H gas has not been taken into account, but this should be included in further research in order to see what is needed to make the demand patterns for H gas feasible.

9.2.5 Investment in transition of grids

About the transition of L gas grids to H gas grids, one can conclude that the transition should be started at some point in order to avoid issues related to the socialization of conversion costs and the impact on the liquidity of TTF. However, as described in the Kiwa/Kema report, the costs of a transition in the Netherlands are high. Also, these costs decrease over time because of the natural phase out of old gas burning appliances.
Phase 1 Background: General functioning L gas system

**Input**
1. What are the main characteristics of the L gas system and how is it operated? (CH2)
2. Which stakeholders are active in the L gas system and what are their interests regarding gas quality? (CH2)

**Output**
1. Concepts and definitions of natural gas systems (CH2)
2. Basic understanding of L gas system (CH2)
3. Main stakeholders and interests regarding gas quality (CH2)

Phase 2 Modeling

**Input**
1. What are the requirements and objectives for the modeling approach? (CH3)
2. What modeling technique can be used to reach those objectives? (CH3)
3. How is this general modeling technique applied to the NWE L gas system? (CH4)

**Output**
1. General modeling approach (CH3)
2. Most urgent supply constraints (CH3)
3. Main system components and capacities (CH4)

Phase 3 Stakeholder behavior analysis

**Input**
1. What possible solutions are being considered among stakeholders and how mature are these solutions in terms of implementation? (CH5)
2. What are the preferences of stakeholders towards these solutions? (CH6)
3. What are the KPI in the L gas system and how would stakeholders respond to changing KPI? (CH6)

**Output**
1. Technical alternatives (CH5)
2. KPI of L gas system (CH6)
3. Stakeholder preferences towards solutions and KPI (CH6)

Phase 4 Integrated scenario analysis and conclusions

**Input**
1. What possible future scenarios for the L gas system can be designed? (CH7)
2. How will the KPI evolve in the different scenarios and how are stakeholders expected to respond? (CH8)
3. How is the physical balance between supply and demand expected to evolve in these scenarios? (CH9)
4. To what extent did the chosen modeling technique approach meet initial requirements? (CH10)

**Output**
1. 5 policy responses and 4 demand profiles in 20 scenarios (CH7)
2. Evolution of KPI in 20 scenarios (CH8)
3. General trends in the L gas system (CH9)
4. Recommendations to Dutch government and EBN (CH11)
5. Reflection on modeling approach (CH10)
10 Reflection on using LP for simulating gas networks

In chapter 3.1 the modeling questions and objectives for this modeling study were formulated. Based on these requirements, Linear Programming was chosen as a means to reach these objectives. This chapter explores to what extent Linear Programming has been an applicable approach to these objectives. It reflects on the general applicability of Linear Programming on simulating gas infrastructures and shortcomings of this approach.

Chapter 10.1 will reflect on the modeling questions that were put on the simulation tool. 10.2 discusses to what extend the model requirements have been met. In chapter 10.3, the main assumptions behind the model are critically evaluated and their consequences to the model outcome are discussed. 10.4 compares the modeling approach chosen with the single point analysis that is currently being used a lot within the industry. This section ends with a conclusion that indicates whether the chosen modeling technique is an appropriate method to simulate flows in a natural gas network and it concludes on the bottlenecks and the shortcomings of this approach.

10.1 Reflection on modeling questions

The objectives for the simulation part were to answer the following three questions:

1. What is the effect of declining production capacities to the technical ability of the system to provide for the demand for a certain type of gas quality? Will an imbalance between demand and supply appear, and if so, on what term?

2. How will different investment options of stakeholders influence the physical flows within the L gas system?

3. How will changing parameters within the system affect the utilization of the Groningen field, storage facilities and conversion facilities?

The simulation tool as designed in this research has been able to answer these questions satisfactorily. By plotting the outcomes of the solved LP problems by software package Linny-R, trends within the L gas system have been identified and the occurrence of imbalances could be closely monitored. Investment options were mostly linear with regards to their physical impact to the system and could therefore be implemented within the LP problem.

The outcomes of the model are clear and understandable. There have been some results in the graphs that have raised doubts about some aspects of the simulation tool. These are discussed in section 8.2. The differences between the scenarios are logical. At some points, certain market developments have arisen earlier or later
compared to comparable studies within the industry. The source of these differences is mainly in modeling assumptions, for example the daily time step, or in the characteristic of the model that it assumes perfect information on demand and optimal use of the system. Chapter 10.3 handles these consequences in more detail.

This last notion reflects on the first modeling question. In a certain way, the model does not per se predict at what time imbalances will appear, it merely explores the maximum boundaries of the system. Earlier imbalances than predicted by this simulation tool might arise if the system is not optimally used. Therefore, using this simulation tool for scenario analysis should always be accompanied by a qualitative analysis of stakeholder preferences and behavior, as executed in this research.

This small last notion on the side, it can be concluded that the simulation tool has been to a large extend able to answer the modeling questions it was designed for.

10.2 Reflection on modeling requirements

The modeling requirements as set earlier in this research were:

- Accessible; easy to understand for external parties
- Workable; easy to adapt to changing parameters
- Quick; short running time to quickly scan effects of changing parameters
- Representative; creating a representative understanding of the L gas system to its users

Although LP fits the relations in a gas infrastructure, in a complex and extensive system like a gas infrastructure, the many relations and the many different nodes in the system result in a large number of constraints and variables. This large number of constraints and formulas would not allow for easy adaptations to the system parameters, it would not be accessible and it would not be verifiably representative to the system. It would merely be a black box model. Therefore, the usage of software providing for an attractive interface is indispensable when simulating the functioning of a gas system by solving the LP representation.

Without the software package Linny-R the workability and the accessibility requirement of the simulation tool would not have been met. Formulas and constraints are translated into distinct processes and products. Parameters can easily be adapted within these processes and products instead of changing and adding the constraints in mathematical form. This has made the simulation tool accessible and workable and it has added to the representativeness of the model as the functioning of the system is clearly visualized.

Running time has been an issue in this research. The dynamics of a natural gas infrastructure are characterized by a wide range of time scales. Some dynamics, like the usage of storage facilities, have a periodic pattern of one year, while within day fluctuations are characterized by hourly fluctuations. This difference results in problems regarding time scales: a small time step is necessary to cover for the hourly fluctuations and a large
look-ahead time in order to cover for the yearly patterns of storages. After changing from an hourly time step to a daily time step, the total simulation time was still 7 hours. This change has led to some implications for the accurateness of the simulation tool, as will be discussed in chapter 10.3

In this simulation study, some extra constraints have been added as an auxiliary to provide for a smaller look-ahead time. For example, it was assumed that all storages were fully injected at the end of the injection season. These assumptions made it possible to use a time scale of half a year instead of a full year. Also, border points were bundled in order to reduce the number of constraints. Eventually, this has resulted in a running time of 2 hours, which is acceptable for the purpose of this study. In a study were more runs are to be executed, for example exploratory modeling, this running time might limit the applicability of LP to this type of problems. Also, when extending the simulation tool to more types of constraints, for example capacity constraints, the modeling time would increase even more.

The adaptation of the look-ahead time and the implementation auxiliary constraints that went with this adaptation has influenced workability of the model. These constraints are not as straightforward as other constraint and need knowledge of the thoughts behind these constraints to adapt. A good example is the modeling of the production cap, as explained in chapter 8.2.1.

As a conclusion, all modeling requirements were met satisfactorily, except the requirement for a quick model. Solving this has had negative impact on the workability and the accessibility of the simulation tool. Also, the assumptions with the adaptations influenced the optimal outcome. When using LP for simulating a natural gas system, this timing issue has to be considered.

10.3 Reflection on main modeling assumptions and its implications

In chapter 5 and chapter 6, a wide range of modeling assumptions has been elaborated on. In this chapter, some of the main assumptions that have influenced the end result or that need reflection in another way will be discussed.

Modeling 183 steps at one time

As discussed before, the choice to model over 183 steps at one time has implications for the results of the model. As can be seen in the graphs of the different scenarios, some increases in certain variables are very high. For example the need for extra nitrogen capacity in Policy response 2 (see Figure 10.1).
Reflection on using LP for simulating gas networks

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Figure 10.1 An example of a steep 'kick-in' caused by a dynamic bound

This is the effect of the large time step. To show this, the storage injection constraint is reflected again below, as derived in chapter 5.

\[
\frac{I_t}{I_{t, \text{max}}} \leq \left( \frac{S_{t-1}}{S_{\text{max, t}}} \right) \cdot \gamma_{t-1}
\]

When extending this formula for multiple time steps in one optimization, the injection capacity at \( t + 182 \) would be constrained by:

\[
\frac{I_{t+182}}{I_{t+182, \text{max}}} \leq \left( \frac{S_{t-1}}{S_{\text{max, t}}} \right) \cdot \gamma_{t-1}
\]

So, the injection capacity at \( t \) equals the injection capacity at \( t + 182 \) (assuming no change in the system e.g. \( I_t(t, \text{max}) = I_{t+182}(t+182, \text{max}) \)). Now extending the formula for the next optimization round, the injection capacity at \( t + 183 \) is defined as:

\[
\frac{I_{t+183}}{I_{t+183, \text{max}}} \leq \left( \frac{S_{t+182}}{S_{\text{max, t+182}}} \right) \cdot \gamma_{t+182}
\]

As can be seen, the injection capacity is constant over the entire time period that is optimized at once. Then, the decrease in injection capacity to the next step is disproportionally high. This leads to the high 'kick-in value' as seen in Figure 10.1. This is also to be seen in the production at Groningen, the capacity of which is a function of the remaining reserves in this field, a decrease that should be linear. However, Groningen production graphs show a stepwise decrease. This stepwise decrease is a result of the 183 look-ahead time.

The implications for the simulation results differ. For Groningen production, the effects are relatively small, as the decline follows a trend over a longer period. For injection and withdrawal capacities of storages, the effects are significant as these capacities are only relevant during half a year each. In the modeling set-up as used in this
study, the injection and withdrawal capacities are therefore not used at all. The main implications to this might arise in times of high demand at the end of a winter. Capacity problems related to a reduced withdrawal capacity because of close to depleted UGS systems is accounted for in this simulation. The only way to solve this would be to decrease the amount of steps the model optimizes at one time and increase the number of time steps the model looks ahead. As discussed earlier, this increases the running time of the simulation tool significantly.

In a competitive market, the utilization of the prioritized source will be maximized before the next source on the priority list will be used.

This assumption has been leading in the design of the merit order of sources. It states that if there is no technical constraint that limits the flow from one source to one demand node, the capacity of a source higher up in the merit order will always be used. This assumption, however, does not include actor behavior that might result in a non-optimal use of the system. Examples mentioned earlier are operators of a UGS system that anticipate a high future demand by strategically maintaining a certain level in their storage, that eventually did not seem to be the optimal way to use this level. Information asymmetry and information incompleteness are the main reasons for these non-optimal uses of the system.

When optimizing the LP objective function within its constraints in the simulation tool, the future demand is known. Therefore, the model can allocate the flows optimal to provide for this demand against the lowest system costs. In the actual world, future demand is not known and neither is the behavior of competing stakeholders. This might result in different outcomes, although in the L gas system the competition on supply is limited and the merit order of supply would not be discussed within the market. But there is always a discrepancy between optimal gas system operation and the actual world. Therefore, the combination with a qualitative stakeholder behavior analysis should always be made to put the model results into perspective.

Storage levels are at their maximum at the beginning of the winter.

A UGS is installed to store natural gas in times of low demand (and therefore low gas price) and to produce this gas in times of high demand (and therefore high gas price). Therefore, it is a valid assumption to assume that UGS systems will be at their maximum level at the end of the injection season. However, at the end of the modeling period this might influence the merit order of supply sources, which is one of the main underlying assumptions in this simulation study.

If Groningen production capacity is insufficient to fill the storages, the simulation tool will work down the merit order to find other, more expensive sources to fulfill the constraint of full storages at the beginning of the winter. Eventually, if other sources are not sufficient, this source might be the very expensive non existing nitrogen production capacity. In real life, one can assume that a new nitrogen production plant will not be built in order to inject in storage facilities as this is not economically viable. The LP simulation set up as originally designed, would optimize these flows correctly and would not fill the UGS with H gas diluted with expensive nitrogen if there was no other way to fulfill demand in any other way. Because of this auxiliary constraint, this situation is
theoretically possible in the current model. Therefore, it is important when evaluating scenarios to see whether an increase in demand for extra nitrogen capacity is not induced by these auxiliary constraints.

**H gas supply unlimited**

Regardless whether it is blended with nitrogen to L gas or used as H gas in a converted grid: Eventually H gas will have to provide for the demand for natural gas within the Netherlands if the production capacity of L gas declines. Not providing gas to households is not an alternative. Therefore, it is a valid assumption to assume sufficient H gas at all times. This assumption has been very helpful in scoping the simulation tool and the research.

**Transport capacity constraints not taken into account**

Considering that the L gas system currently provides for all demand and that demand is not expected to increase, and considering the importance of a secure gas supply, pipeline capacity has not been taken into account in the simulation tool structurally. Rather, transport capacity at bottlenecks has been set at a maximum, for example at the pipeline connecting the Groningen system with the blending station at Wieringermeer. Including these constraints was the result of fixing unexpected model outcomes rather than a careful selection in the beginning of the research.

In retro perspective, this assumption has been a very critical one. Including transport capacity would have increased the complexity of the simulation tool significantly, thereby reducing its advantage towards the more sophisticated planning tools as used by GTS in terms of the workability, modeling speed and accessibility. But at the same time it would have added to the conclusions in this research. The conclusions of the simulation tool will always have to be checked by an extra analysis whether the flows are actually physically possible.

With the objective of the simulation tool in mind, to make predictions about the balance between supply and demand for a period of 20 years, including the transport capacities as exact as some authors introduced in chapter 3.2 would not work. However, just assuming that there are no transport capacities at all is not an option either. The selection of what transport capacities need to be taken into account could have been more structured and thought-out. When improving the simulation tool this would be the first recommendation: do more research into the capacity bottlenecks within the system, critically select those that limit the systems functioning and implement those into the simulation tool.

**Extra nitrogen capacity at constant costs**

When running the model, new non-existing nitrogen facilities were implemented in the model at very high costs. Being the last supply source of the merit order of sources, these facilities would only be used when there was no
other way to supply that specific demand. The capacity of these new facilities is unlimited so that it shows the peak capacity needed to satisfy demand.

For the optimization process, it does not matter whether it produces 10 units at once or 1 unit in 10 time steps, if the price is constant. For the real life costs, however, this might have large implications if the capacity of once facility would be, for example, 5 units per time step. In the first situation, two facilities would have to be build while in the second situation one extra facility would do. But sometimes both could be possible, for example in the situation of a production cap at Groningen, where you could decide to either produce at full capacity first and later nothing (situation 1) or produce at a constant average rate (situation 2). Therefore, this should be modeled differently.

One way to do this would be to implement multiple extra nitrogen facilities, each with a capacity of 150,000 m$^3$/hour but all with different costs. In this way, the optimization would look to flatten the peaks in nitrogen demand as much as possible, as it would optimize the use of the first new location before it would use the second, and so on.

10.4 Reflection of tool vs. single point analysis

In chapter 1, three main reasons why the generally used single point analysis in combination with a LDC would not be sufficient to meet the modeling requirements. These 3 reasons were:

- Single point analysis is place independent; all components are aggregated per function
- Single point analysis does not allow for quality ranges; it assumes one static quality
- Single point analysis does not make use of time series, thereby ignoring fluctuations in demand

Reflecting on these 3, the model has been variably successful in implementing these shortcomings.

Place independency has been accounted for better than the single point analysis. Especially the physical constraints, e.g. the existence of a connection between two nodes (and the direction of this connection) accounts for this advantage above single point analysis. However, by letting go of capacity constraints the place independency is not yet totally overcome in the simulation tool.

The demand for quality ranges has been met satisfactorily and this has appeared as one of the main advantages of LP in comparison to single point analysis. This definitely adds to the modeling technique, and with the changing gas qualities within the Dutch natural gas infrastructure because of LNG and green gas this will become more and more important.

Time series have been used extensively in the research and was one of the main reasons for the many iterative steps, as the modeling time was one of the bottlenecks in this research. The result is that the outcome of the
model is not only an answer to the question whether it would provide peak demand or not (as with single point), but it also provides the pattern with which this demand is delivered. However, fluctuations in demand with respect to sudden changes in production capacities have not been taken into account. In this research, start-up time and up scaling time of production (e.g. production at t dependent on production at t-1) has not been taken into account. However, there are ways to linearize this into an LP problem.

On the downside, modeling a natural gas network as an LP problem is, even in the simplified form that this research has chosen for, much more time consuming than a single point analysis. Also, the many auxiliary constraints and nodes in the model have reduced the accessibility of the model for someone who did not work with this model yet. In its simplicity, the single point analysis can be applied quicker and it is easier to understand for someone new.

In chapter 3, the simulation tool in this research has been positioned in between the single point analysis and the complex planning models used by TSO's. It should be considered case by case what modeling approach fits the requirements. This research has set the first step in the development of a modeling approach that goes further than the single point analysis, but that is still workable in such a way that it can be used to model over a long period of time with different scenarios. This is a relevant contribution to the long list of mathematical optimization methods as used for natural gas systems.

10.5 Conclusions

The model as presented in this research is not ready to be used on a large scale within the industry yet. For this, too many imperfections are still in the model that need to be solved. But even with the many imperfections in the current model, the model has resulted in some very clear and interesting trends for the future of the L gas system. Therefore, the current model has a great potential to be improved in order to overcome these imperfections. The modeling software has provided the model the actual accessibility to allow subsequent researches to actually do this. For those researches, this master thesis will provide abundant guidelines and suggestions for improvement.

The main problems arising when using LP to simulate the functioning of a gas system are induced by the requirement to the model to be quick and auxiliary constraints in order to fulfill this requirement. When solving this problem, the majority of the implications of these assumptions would be mitigated. Solutions might be in using a different solver to solve the LP problem as used in the software packet.

Besides the trade-offs in the modeling process between accurateness and speed of simulation, and besides the problems related to the production cap, it appears that the underlying assumptions to simulate gas flows in a natural gas system by expressing it as a LP problem is satisfactorily when the physical boundaries of the gas system are to be explored. Qualitative analysis of stakeholder interests and stakeholder behavior is essential in order to translate the outcomes of the model towards predictions for the real life functioning of the system.
11 Conclusions and Recommendations

In chapter 2, two main research questions have been presented. In this chapter, the preceding chapters are summarized in an answer to these questions. Again, a distinction has been made between the case specific questions regarding the L gas system in North West Europe, and the general scientific question related to using Linear Programming to simulate the flows within a natural gas system. The main problem statement as presented in chapter 2 is:

With the future decline in L gas supply, there is uncertainty in the North West European L gas market about the security of supply, which might lead to diversifying behavior on the demand side.

11.1 Conclusions and recommendations for the L gas system

This chapter aims to answer the main research question:

What scenarios can be designed for the L gas market and how is the physical balance between demand and supply maintained by stakeholders’ investment decisions in these scenarios?

Answer: In the L gas market, the speed and the order of a transition of (parts of) the L gas grid to a H gas grid determines to a large extent the investment that is needed to maintain the balance between demand and supply within the L gas system. This investment would be in the form of an extra nitrogen production facility and this would increase the conversion costs. However, any transition of grids would be cost intensive and would require central coordination of the Dutch as the safety hazards of this operation are high and the experience in this...
process is limited. Therefore, the importers of Dutch gas are reluctant to plan large scale transition of their grids, also because they do not foresee problems regarding the supply of L gas on the short to medium term.

For the Dutch government, the situation in which a transition of the Dutch grids is postponed until after 2030 would best safeguard the public values of reliable natural gas supply and maximum income from production from the Groningen field. In this situation, extra nitrogen production capacity is necessary to provide sufficient supply of L gas. This investment will have to be in the region of €90 million - €300 million dependent on the speed of a transition in the importing countries. These facilities would need to be operational from 2025 onwards.

In other scenarios the Dutch grids will be converted from L gas to H gas grids too. In this research, this transition would start in 2022, and needs delicate planning and coordination. Therefore, it is advised that the Dutch government should take up a central, coordinating role in this process.

No matter what policy response and or demand profile will be chosen, it is clear that the Groningen field will have lost its function as the main source of flexibility in the North West European L gas by 2020. This function will be taken over partly by existing L gas storages, but to a large extend this flexibility will have to be provided by H gas.

Throughout this research, many recommendations have been mentioned. The main recommendations for the Dutch government are:

11.1.1 Recommendation: Increase Transparency towards gas importing countries
In Belgium, France and Germany, TSOs are not prepared for a transition of their grids on a large scale. In Germany, transition is limited to compensate for the decrease in domestic production, whereas in Belgium new consumers are being connected to the L gas grid every year. Transition is a costly and a complex operation, which makes it unlikely that this transition is executed if it is not really necessary. In order to avoid the transition in these countries to be not optimal, which can be either too slow or too quick, a transparent dialogue to the TSO in Germany and in Belgium should be opened in order to coordinate this transition cooperatively. The incentives and objectives are mutual and therefore transparency is not expected to have negative effects.

11.1.2 Recommendation: Take coordinating role in a transition
The transition of L gas grids to H gas grids is a delicate process that needs close cooperation of all parties involved. The safety risks are high and the operation is typically executed in an area with a lot of houses. Also, there is no incentive for DSOs to take the first steps as the costs of a transition decrease rapidly over time. Therefore, it is important to control this process. The Dutch government should take a coordinating role in this process in order to safeguard the safety.

11.2 Conclusions and recommendations for the modeling approach
This chapter aims to answer the main research question:
What method can be used to simulate the flows within a natural gas system in a workable and accessible model? How satisfactorily is this method and what are shortcomings to this method?

Answer: This research has used Linear Programming as a means to simulate the L gas network. It appeared that most of the constraints were linear, or could be adapted to a linear constraint without losing too much of its accurateness. The use of LP is preferred above generally applied modeling approaches. When using LP, the use of a software program with an attractive interface is essential for the required workability and accessibility. In this research, the software package Linny-R has been used.

It can be concluded that Linear Programming is useful to simulate gas flows within a natural gas system only if the results of the simulation are combined with a more qualitative analysis of stakeholder preferences. As the simulation with the objective function and the constraints used in this research only provides for an optimal use of the system, this qualitative analysis provides for the consequences when this system is not used optimally. This combination of analyses is essential to provide useful conclusions.

The hourly fluctuating demand pattern in relation with the seasonal fluctuation of storages make it hard to control the number of time steps that are to be used as a look-ahead, and therewith to control the total numbers of variables within the simulation. This has led to problems regarding the solving time of the model and therewith the workability of the simulation tool. This same workability and accessibility was partly lost when shortcuts and auxiliary constraints are to be used in order to reduce the modeling time.

Using a weekly time scale for the long term simulation and only zoom in at bottlenecks with a daily time scale has been suggested by a supervisor during this research. The limited time available for this research did not allow for this additional research step to be made within this research. Therefore, it is recommended for further research. This could be very helpful in further verifying and validating the model; before the model can be used on a large scale, more attention will have to be paid to the validation and the verification of the model.

11.3 Recommendations for further research

Based on the results of this research this chapter introduces possibilities for further research.

11.3.1 Include transportation constraints

Although the assumptions underlying the decision not to take transportation constraints into account are valid, I think transportation constraints could be one of the reasons for the described difference. At some points, transportation constraints have already been taken into account. Taking the result as described above into account, the transportation constraints around the Groningen field would have to be looked into in further research.

With the objective of the simulation tool in mind, to make predictions about the balance between supply and demand for a period of 20 years, including the transport capacities as exact as the authors introduced in chapter 3.2 would not work. However, just assuming that there are no transport capacities at all is not an option either.
The selection of what transport capacities need to be taken into account could have been more structured and thought-out. When improving the simulation tool this would be the first recommendation: do more research into the capacity bottlenecks within the system, critically select those that limit the systems functioning and implement those into the simulation tool.

11.3.2 The availability of H gas for blending

One very clear conclusion from this research is the increased demand for H gas for blending purposes on a relatively short term. It is interesting to see whether this increase can be delivered from existing sources or whether extra investment is needed to provide for this demand.

11.3.3 Extend the model to problems regarding the PE-number

One of the main advantages of the simulation tool is that it enables different quality types of natural gas to be mixed under the constraint of a quality ranges for the gas outflow. This makes the simulation tool interesting for other researches. Because of the increasing share of LNG and green gas in the NWE natural gas systems, multi gas systems are getting more and more attention. The modeling approach introduced in this research typically fits these problems as it allows for different qualities.

One of the main problems for gas flows in the future is considered to be the relatively large PE-number in some LNG gasses. The modeling approach used in this research would fit this problem.

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### Appendix A List of Interviewees

<table>
<thead>
<tr>
<th>Organization</th>
<th>Name of Interviewee</th>
</tr>
</thead>
<tbody>
<tr>
<td>GasTerra</td>
<td>Sjaak Schuit</td>
</tr>
<tr>
<td>Gasunie</td>
<td>Sander Huizinga</td>
</tr>
<tr>
<td>Shell</td>
<td>Joram Meijerink</td>
</tr>
<tr>
<td>ExxonMobil</td>
<td></td>
</tr>
<tr>
<td>Zantingh (appliances producers)</td>
<td>Rob van der Pol, Rein Tichelaar</td>
</tr>
<tr>
<td>NMa</td>
<td>Ir. Yoeri van der Drift</td>
</tr>
<tr>
<td>Linde Gas (Nitrogen Producer)</td>
<td>Ir. Hendrik de Wit</td>
</tr>
<tr>
<td>CREG (Regulator Belgium)</td>
<td>Ir. Geert van Hauwermeiren</td>
</tr>
<tr>
<td>Fluxys (TSO Belgium)</td>
<td>R. van Beurden</td>
</tr>
<tr>
<td>Gasunie-DU (TSO Germany)</td>
<td>Dr. Ing. Michael Kleemix</td>
</tr>
<tr>
<td>GTS</td>
<td>3 analysts network development department</td>
</tr>
<tr>
<td>Project team EDGaR</td>
<td>Bert Pleizier</td>
</tr>
<tr>
<td>Energy Delta Institute</td>
<td>dr.ir. Martien Visser</td>
</tr>
<tr>
<td>EBN</td>
<td>Multiple employees within EBN</td>
</tr>
</tbody>
</table>
Appendix B German Production capacity per region

<table>
<thead>
<tr>
<th>Jahr</th>
<th>Gebiet Elbe-Weser (ohne Altmark)</th>
<th>Gebiet Weser-Ems</th>
<th>Deutschland insgesamt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Produktion</td>
<td>Veränderung</td>
<td>Kapazität</td>
</tr>
<tr>
<td></td>
<td>Mio. m³</td>
<td>%</td>
<td>1000 m³/a</td>
</tr>
<tr>
<td>2011</td>
<td>4902,0</td>
<td>3,5%</td>
<td>613,4</td>
</tr>
<tr>
<td>2012</td>
<td>5072,5</td>
<td>3,5%</td>
<td>613,4</td>
</tr>
<tr>
<td>2013</td>
<td>4728,0</td>
<td>3,5%</td>
<td>583,7</td>
</tr>
<tr>
<td>2014</td>
<td>4555,6</td>
<td>3,5%</td>
<td>603,3</td>
</tr>
<tr>
<td>2015</td>
<td>4472,5</td>
<td>3,5%</td>
<td>609,8</td>
</tr>
<tr>
<td>2016</td>
<td>4300,4</td>
<td>3,5%</td>
<td>577,4</td>
</tr>
<tr>
<td>2017</td>
<td>3867,3</td>
<td>10,6%</td>
<td>480,6</td>
</tr>
<tr>
<td>2018</td>
<td>3154,3</td>
<td>15,9%</td>
<td>427,6</td>
</tr>
<tr>
<td>2019</td>
<td>2844,2</td>
<td>9,9%</td>
<td>382,1</td>
</tr>
<tr>
<td>2020</td>
<td>2548,6</td>
<td>10,4%</td>
<td>340,1</td>
</tr>
<tr>
<td>2021</td>
<td>2318,0</td>
<td>9,0%</td>
<td>306,8</td>
</tr>
<tr>
<td>2022</td>
<td>2033,9</td>
<td>12,3%</td>
<td>266,1</td>
</tr>
</tbody>
</table>

Source: WEG (2012)
## Appendix C Capacities of Storage Facilities

<table>
<thead>
<tr>
<th>Location</th>
<th>Calorific value</th>
<th>Working Volume</th>
<th>Injection capacity</th>
<th>Withdrawal capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGI Alkmaar</td>
<td>36</td>
<td>500 mcm</td>
<td>3,6 GWh/ day</td>
<td>36,0 mcm/ day</td>
</tr>
<tr>
<td>Norg</td>
<td>35,17</td>
<td>3000 mcm</td>
<td>30,0 GWh/ day</td>
<td>50,2 GWh/ day</td>
</tr>
<tr>
<td>Epe Nuon</td>
<td>36</td>
<td>220 mcm</td>
<td>3,6 GWh/ day</td>
<td>13,7 GWh/ day</td>
</tr>
<tr>
<td>Epe RWE</td>
<td>36</td>
<td>553 mcm</td>
<td>4,8 GWh/ day</td>
<td>9,1 GWh/ day</td>
</tr>
<tr>
<td>Zuidwending</td>
<td>35,17</td>
<td>200 mcm</td>
<td>19,0 GWh/ day</td>
<td>38,0 GWh/ day</td>
</tr>
<tr>
<td>Gournay sur Aronde</td>
<td>38</td>
<td>1280 mcm</td>
<td>12,0 GWh/ day</td>
<td>28,2 GWh/ day</td>
</tr>
<tr>
<td>Nüttermoor</td>
<td>38</td>
<td>1069 mcm</td>
<td>11,6 GWh/ day</td>
<td>11,6 GWh/ day</td>
</tr>
</tbody>
</table>
Appendix D1 The simulation tool – North Netherland
Appendix D2 The simulation tool – West Netherland
Appendix D3 The simulation tool – Ommen area
Appendix D4 The simulation tool – Germany
Appendix D5 The simulation tool – Belgium and France
Using Linear Programming to simulate the gas flows in the North West European L cal gas system

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ABSTRACT
The main source of the North West European L cal gas system is the Groningen gas reserve in the Netherlands. The declining production capacity of this gas reserve has implications for the ability of this system to balance demand and supply. Stakeholders have different alternatives to maintain this balance towards 2030. Current modelling approaches are either too simplistic or too complicated to evaluate this long term evolution of the L gas system. This paper presents a modelling approach that positions itself successfully in between these two existing models. By assigning a merit order of sources within 5 types of constraints this paper has assessed this ability with Linear Programming. It appears that only a fast transition of L cal grids into H cal grids could avoid the necessity of an increase in nitrogen production capacity from 2025 on. Also, H cal gas should replace the function of the Groningen field as the main source of flexibility within the system. This modelling approach can be applied generally as it fits the general trend towards national gas systems with a wider variety in gas qualities.

1. Introduction

In the North West European transmission networks the following gas quality types are identified (Gasterra 2012):

• **L gas.** Gas with a relatively low calorific value. Gasses with a Wobbe index of 42,5 – 47 MJ/m³.

• **H gas.** Gas with a relatively high calorific value. Gasses with a Wobbe index of 48 – 56 MJ/m³.

• **G-gas.** G-gas (Groningen-gas) is the term used for the gas from the large gas field in Groningen. Its Wobbe index is Wobbe of 43,8 MJ/m³. Therefore, it is within the quality range for L gas.

The L gas system in North West Europe is facing the challenge of handling the production decline of the Groningen gas reserve, the main source for L gas in North West Europe (Visser 2011). With about 70% of the L gas in this system produced from this field, this future decline has put down questions about the ability of this system to maintain the balance between demand and supply on the long term.

In the L gas system different gas qualities are mixed within the quality range as set in the netcodes (GTS 2011). The main quality parameter is the Wobbe-index.
Three main physical alternatives to mitigate the impact of the decline in Groningen production capacity exist. An increase in nitrogen capacity to dilute H gas to L gas, increase storage capacity to increase peak capacity and a transition of L gas grids to H gas grids.

Stakeholders within the system are uncertain about the timing and the impact of the decline in Groningen production on the ability of the L gas system to balance demand and supply and on the impact of the different alternatives (CREG 2007, CREG 2010). Stakeholders in the L gas system have made use of models to assess this ability.

Single point analysis has been used in combination with a Load Duration Curve to compare peak capacity with peak demand. Single point analysis is easy to apply, easy to adapt and easy to understand.

Although the single point analysis is good method to quickly compare capacities and demand, it does not account for many complexities and interdependencies within the North West European L gas system because of a number of reasons.

- Single point analysis is place independent; all components are aggregated per function
- Single point analysis does not allow for quality ranges; it assumes one static quality
- Single point analysis does not make use of time series, thereby ignoring fluctuations in demand

In this paper, a specific Linear Programming problem is introduced that mitigates the problems of single point analysis but that maintains the advantages of the single point analysis.

Section 2 gives a brief overview of the use of Linear Programming in natural gas networks. Section 3 and 4 presents the LP problem for this model. Its main components, being a merit order of supply sources and the choice for technical constraints, are presented in section 5 and 6. In section 7, Liny-R is introduced, a software package in which the model has been designed. Section 8 presents the results of this model when it is applied to the North West European L gas system. Finally, section 9 describes the advantages and the disadvantages of this modeling approach.

2. Network optimization in natural gas

Using Linear Programming for natural gas network optimization has been used extensively in scientific literature. Zheng, Rebennack et al (2010) have presented a detailed discussion on the use of optimization models on three different key applications: the natural gas production, the natural gas transportation and the natural gas market. Within the Netherlands, the study “Math in Gas and the art of linearization” (van der Hoeven 2004) gives a very detailed description of how the many non-linear relations within a natural gas network can be linearized to make them applicable.

In modeling a natural gas network by optimization methods, the tradeoff between level of accurateness and accessibility of the model is well understood. Midthun (2007) describes this tradeoff “between accurately describing the properties of the transportation network, and being able to solve the model”. The studies introduced above pursued to model the exact capacities and pressures within natural gas pipelines as precise as possible in order to operate these pipelines. This research focuses on the long term ability of the L gas system to match
supply and demand. Therefore, different requirements to the LP model for this study exist.

Butler and Dyer (1999) have identified timing issues in their modeling study in which they wanted to give operational planning advice on both short term and long term, being 1 year. They had to aggregate their daily time step in order to maintain the short modeling time and therewith the workability of their model. Although criticized by Midthun (2007), Cremer, Gasmii and Laffont (2003) have assumed one static capacity per pipeline. This would not take into account the difference between minimal pipeline pressure and maximum pipeline pressure, for example, but it does simplify the model and therewith the workability of the model.

This search for the right level of complexity in the model is best described by Mulder and Zwart (2005): “A model of the gas market is a description of the real market, capturing its fundamental features. To construct an empirically well founded model, it is necessary to consider the essential characteristics of the European gas market.” In order to achieve the specific requirements to the model in this research it is key to find these essential characteristics for the European L gas system.

3. LP problem formulation

The modeling approach is defined as: “Optimization of utilization of supply sources according to a merit order, to supply demand within the technical constraints of the system”. In this research, this has been modeled with the following LP problem:

\[
\begin{align*}
\text{MINIMIZE} & \quad \alpha P_{1e} + \beta P_{2e} + \gamma P_{3e} + \delta P_{4e} + \varepsilon P_{5e} \\
\text{Subject to:} & \quad P_{1e} + P_{2e} + P_{3e} = D_{te} \\
& \quad P_{1e} \leq C_{1e} \\
& \quad \frac{H_{te}}{H_{e}^{\text{max}}} \leq \left( \frac{S_{e} - 1}{H_{e}^{\text{max}}} \right) * P_{3e, t-1} \\
& \quad S_{e} = S_{e-1} + I_{e} - W_{e} \\
& \quad S_{e} \leq W_{W_{e}^{\text{max}}} \\
& \quad S_{e} \geq 0 \\
& \quad \frac{P_{1e}}{P_{1e} + P_{2e}} Q_{1e} + \frac{P_{2e}}{P_{1e} + P_{2e}} Q_{2e} \leq Q_{\text{max}} \\
& \quad \frac{P_{1e}}{P_{1e} + P_{2e}} Q_{1e} + \frac{P_{2e}}{P_{1e} + P_{2e}} Q_{2e} \geq Q_{\text{min}} \\
& \quad I_{e} = \sum_{t=1}^{n} q_{t} P_{t, e} \\
& \quad q_{t} = \begin{cases} 1, & \text{when } P_{t} \text{ is coupled to } I \\ 0, & \text{when } P_{t} \text{ is not coupled} \end{cases}
\end{align*}
\]

With
\[
\begin{align*}
\alpha, \beta, \gamma, \delta, \varepsilon & = \text{virtual costs reflecting merit order} \\
P_{i} & = \text{production in production node } i \text{ at } t \\
D_{i} & = \text{demand at demand node } i \text{ at } t \\
C_{i} & = \text{production capacity at production node } i \text{ at } t \\
I_{i} & = \text{Injection capacity in storage } i \text{ at } t \\
l_{i} & = \text{max injection capacity in storage } i \text{ at } t \\
S_{i} & = \text{Storage level in storage } i \text{ at } t \\
S_{i}^{\text{max}} & = \text{maximum working volume of storage } i \\
\gamma_{i, t} & = \text{parameter translating stock ratio into injection ratio} \\
Q_{i} & = \text{gas quality at production node } i \text{ at } t \\
Q_{\text{max}, t} & = \text{max allowed Wobbe value in the network at } t 
\end{align*}
\]

4. Model set-up

The optimisation model is set to optimize 183 time steps ahead. One time step equals one day in this research. One optimization period is half a year. This period is chosen to make sure that the
UGS fill up during the injection season. This decision has implications for the objective function and the constraints. The new objective function and the first constraint have been expanded now:

\[ \text{MIN} \]

\[ \alpha P_{1c} + \beta P_{2c} + \gamma P_{3c} + \delta P_{4c} + \epsilon P_{5c} + \alpha P_{1c+1} + \gamma P_{3c+1} + \delta P_{4c+1} + \epsilon P_{5c+1} \]

\[ P_{1c+1} + P_{2c+1} + P_{3c+1} = D_{c+1} \]

\[ P_{1c+1} + P_{2c+1} + P_{3c+1} = D_{c+1} \]

A second type of constraints in the model is \textbf{production constraints}. Production of natural gas is limited by the technical withdrawal capacity of these fields, and the remaining reserves within the field. Typically, the withdrawal capacity will decrease over time when the reserve gradually gets depleted.

Also, nitrogen production for quality conversion and injection and withdrawal rates for Underground Gas Storages are of this type. Nitrogen production is constrained by its production capacities. Storage injection and withdrawal capacities are not only constrained by technical limitations, but also by the pressure within the storage. Injection capacity is at its maximum when the pressure in the field is low, e.g. when the storage level is relatively low.

In this type of constraints, the maximum production rate at time \( t \) is dependent on the actual amount of gas present in the storage at this time. However, in a linear optimization, it is not possible to find an optimum if two values are interrelated to each other. In this simulation, this non-linear relation is expressed in a linear way by using the storage level of one time step earlier than the actual time of simulation. In this way, the non-linearity of this relation has been changed into a linear one.

A third type of constraints is \textbf{storage constraints}. Underground gas storages (UGS) are used to provide for both the seasonal and the daily fluctuations in L gas demand by storing gas in times of low demand or low price levels, and delivering gas in times of peak demand or peak price. A UGS system is constrained by its injection capacity, its storage capacity (= Working Volume) and its withdrawal capacity. Again, injection and withdrawal capacity are dependent on the pressure within the Storage.

5. \textbf{Choice for 5 constraints}

In the LP formulation above the optimization model has been constrained to 5 constraints. These constraints are:

1. Demand constraints
2. Production constraints
3. Storage constraints
4. Quality Constraints
5. The existence of physical connections

Firstly, it is assumed that the system has to fulfill the demand for L gas at any given time. As L gas is mainly supplied to households that use it to cook and to heat their water and their houses, people are dependent in their daily lives on this supply. Disruptions in supply are not accepted.
The fourth type of constraints used in this model is quality constraints. The main parameter in this system is the Wobbe-index. This Wobbe range sets a minimum value and a minimal value for the Wobbe after this blending station. For modeling reasons, the Wobbe is assumed to be linear, e.g. the Wobbe of two flows with equal volume is the average of their two Wobbe values.

The final and most obvious type of constraints in the system is the existence of physical connections. The distribution of gas is constrained by the existence of pipelines from put to pit. As the L gas system is typically unidirectional, roughly from North to South, the existence of a connection between to nodes is essential to allow for this flow.

This type of constraints is used to combine the other constraints discussed in this section. This type of constraints forms the cement of the simulation as it connects all system components to each other.

6. A merit order of supply sources

The modeling approach is defined as: "Optimization of utilization of supply sources according to a merit order, to supply demand within the technical constraints of the system". Next to constraints, the second main component of this approach is the merit order of sources. This merit order forms the objective function of the LP problem.

As there are different supply sources within the North West European L gas system, not all supply sources will produce at full capacity. In a fully competitive market, a supply source would produce gas if its marginal producing costs would be lower than the market price. In the North West European L gas system, this theory does not entirely work due to historic reasons and the specific characteristics of the Groningen gas field.

In this research, a merit order of supply sources is assumed. This means that all supply sources are prioritized and that a supply source is not used before production from sources further up in the merit order is constrained by either production capacity or one of the other constraints.

This leads to the following merit order of supply sources according to which the different sources are utilized (Bijl 2012):

1. L gas production of Small fields (sometimes off spec H gas) and German production
2. L gas production in Groningen
3. L gas in UGS
4. H gas blending (until upper Wobbe range)
5. H gas + nitrogen

7. Software package Linny-R

The general LP problem as presented in this paper is the result of a modelling study with modelling software Linny-R, developed at the TU Delft. This modelling software provides an attractive interface in which products and processes can be linked. For each of these nodes, capacities costs and other attributes can be assigned. The software package returns this input into the specific LP problem to be solved by a solver.

In order to achieve a workable and easily understandable and adjustable simulation tool using LP this software package has been

8. Simulation results

Applying the general simulation method as described in this paper to the L gas system in
North West Europe, it appears that extra nitrogen capacity would be needed in 2025 in order to provide for the L gas demand as can be seen in figure 1. This need for extra capacity could be avoided if the L gas grids in Belgium, France and Germany would be converted to H gas grids from 2022 on, with such a speed that in 2031 90% of their grids is converted. Also, the Dutch grids should be converted to a 50% conversion rate in 2031 to avoid this nitrogen demand. A optimal solution for society would be a combination of moderate investment in N2 capacity in combination with a transition starting abroad.

Secondly, the Groningen production field will lose its function as a swing producing field as it is expected to produce with a load factor 1 from 2021 on, see figure 2. H gas will have to provide for the flexibility within the system in combination with the existing L gas storages. It needs to be assessed whether the current H gas system will be able to provide for this flexibility.

### 9. Reflection on modeling approach

The model presented in this paper appeared to be a good method for a workable and accessible simulation tool for physical flows within a general natural gas system. The shortcomings of more simplistic methods were overcome while maintaining an acceptable running time and an attractive and understandable model. The main shortcomings of more simplistic methods that were overcome were:

- Place independency; more simplistic methods aggregate all components per function
- Allowance for quality ranges; more simplistic methods assumes one static quality
- Use of time series; more simplistic methods ignore fluctuations in demand

Shortcomings to the method were that the hourly fluctuations in demand against the seasonal fluctuations of storages make that a large look-ahead time needs to be used, decreasing the speed of the simulation tool and therewith the workability of this tool. This was compensated for by auxiliary constraints to be able to use a smaller time step. Subsequently, these auxiliary
constraints reduced the accessibility of the model for external people.

Secondly, LP can only be used to simulate the flows within a system if this system is optimally used. Therefore, simulating the flows within a natural gas system with LP should always be used in combination with a more qualitative analysis of stakeholder behavior within the system in order to put the outcomes of the model within the right behavioral perspective. Bijl (2012) is an example of a research at which this integrated approach is applied.

The simulation tool in this research has been positioned in between the single point analysis and the complex planning models used by TSO's. It should be considered case by case what modeling approach fits the requirements. This research has set the first step in the development of a modeling approach that goes further than the single point analysis, but that is still workable in such a way that it can be used to model over a long period of time with different scenarios. This is a relevant contribution to the long list of mathematical optimization methods as used for natural gas systems.

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