Finding robust investments for the Dutch gas distribution infrastructure in 2050 by a scenario study

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Abstract:
In the changing Dutch energy market, the ageing gas distribution grid needs investments. There is, however, a large uncertainty regarding certain aspects that affect the future role of this gas distribution grid, such as the eventual share of biomethane in the gas mix, whether power-to-gas will take-off and the expected lifetime of the grid. Hence, it is currently unclear what investments need to be made for the gas distribution infrastructure in order to cope with future changes.
To find out how the future may unfold for the Dutch gas distribution infrastructure in 2050, four scenarios have been developed. Two key forces – a key force is a factor that has a large impact on the gas distribution grid but great uncertainty exists regarding its outcome – were chosen, namely "perceived energy resource scarcity" and "willingness and ability to reduce greenhouse gas emissions". Each scenario sketches the future Dutch gas infrastructure by defining, among others, the extent to which biomass will be used to produce biomethane, whether fossil fuel is allowed to be burned locally, and what types of gas will flow through the gas grid. With these scenarios at our disposal, in the next research step, we will establish the impact of the scenarios on the gas distribution grid – i.e. what the layout will be and the corresponding costs – and the accompanying biomethane infrastructure. For this, 3 typical locations were chosen: a rural region, an urban region, and an intermediate region. Through a multi-objective optimization – with maximizing net present value, maximizing biomethane production, and maximizing CO2 emission reduction as objectives – the possible layout of the gas distribution grid and the biomethane infrastructure will be determined for each region. The study's aim is to find similarities in investments among the different layouts, to come to robust investments for the gas distribution infrastructure.

Keywords:
Gas distribution grid, scenario development, biomethane supply chain, multi-objective optimization.

1. Introduction

The gas infrastructure forms a crucial part of the Dutch energy system; about half of the primary energy demand is met by natural gas. The gas grid can be divided in two parts. First, the transportation grid, which transports natural gas at high pressures (it is operated at 40 and 66 bar) over long distances throughout the Netherlands. Second, the distribution grid which distributes the natural gas at low pressures (the operating pressures range from 30 mbar to 8 bar) over short distances from the transportation grid to households and other consumers. About 98 percent of households is connected to the gas distribution grid and it is operated by Distribution Service Operators (DSOs). This paper focuses on the gas distribution infrastructure.

It is expected, that the Dutch energy market will change significantly in the near future, and with this the gas distribution infrastructure. First of all, the end of domestic gas production is now in the horizon of the industry. As a consequence, gas imports are expected to rise. The imported gases have a different gas quality than the domestic natural gas, and the gas distribution infrastructure and its connected appliances might have to be adjusted. Furthermore, the Dutch government has decided to reduce greenhouse gas (GHG) emissions by increasing the production of renewable energy, among which a significant share of biogas or biomethane – which is biogas upgraded to natural gas quality. The biomethane will most likely be injected in the gas distribution infrastructure. Investments in the gas distribution infrastructure are required to facilitate the injection of biomethane. At the same time, the gas distribution network is ageing and needs to be upgraded, replaced, or decommissioned. In order to cope with these changes, investments are needed for the gas distribution infrastructure.

Investments made last for 40-80 years and thus the choices made now shape the gas distribution infrastructure in 2050. Investments are needed in the short term to make sure that the infrastructure can cope with future requirements. However, it is not clear yet what exactly these requirements are. Therefore, it is difficult to determine what to invest in, how much and when. DSOs face a real dilemma. Investing now may enable the transition towards a more sustainable energy system; but it is likely that part of these investments will be unproductive. Postponing investments, which can be preferable from an investment efficiency point of view, may stifle developments and slow down the transition. This is the DSO's dilemma.

CE Delft wrote a report that aimed to help the DSOs in dealing with their dilemma [3]. It investigated what the impact on Dutch energy infrastructures will be, when the EU target of 90% CO_2 emission reduction in 2050 compared to 1990 becomes reality. Three scenarios are described in this report which differ from each other in the technologies used to meet the projected energy demand. Another report on the future of energy systems was written by ENA [5], which focussed on the future of the gas grid in Great Britain, and takes a strong CO_2 emission reduction by 2050 compared to 1990 as a boundary condition. Four scenarios for the year 2050 are derived which differ from each other in whether two technologies become available, namely Carbon Capture and Storage (CCS) and large scale energy storage (diurnal electricity and seasonal heat storage). Furthermore, the Forschungs Verbund Erneuerbare Energien [14] describes an energy system for Germany in the year 2050, which is based on 100% renewable energy and heavy efficiency improvements, in order to reduce CO_2 emissions by at least 90% compared to 1990. The European Gas Advocacy forum developed three pathways for the European energy system to achieve 80% CO_2 reduction [15]. The scenarios differ from each other in the extent to which energy sources are employed, which consist of: fossil energy in combination with CCS, nuclear energy, and renewable energy sources.

The mentioned scenarios and pathways take a strong reduction of CO_2 as a boundary condition. As mentioned by CE Delft [3], these strong reductions in CO_2 emissions will only occur when there is sufficient public and political support for these changes. Whether this will be the case is highly uncertain. Furthermore, none of these scenarios have a focus on the (Dutch) gas distribution grid.

Therefore, the goal of our research is to develop future scenarios for the Dutch gas distribution infrastructure in which CO_2 emission is not taken as a boundary condition. This is done in the first part of the paper, which is composed of sections 2, 3 and 4. In the second part, composed of section 5, it is described how the scenarios will be used to derive required investments for the gas distribution infrastructure. Ultimately, we hope to help the DSO's in dealing with their investment dilemma.

The outline of this paper is as follows. Section 2 describes the method to come to the scenarios. Section 3 underpins the choices made to come to the scenarios. Section 4 describes the developed scenarios. Finally, in section 5 it is described how the impact of these scenarios on the gas distribution system will be assessed in follow-up research, how the required investments will be determined, and some preliminary results will be shown. Finally, section 6 draws conclusions about the presented research.

2. Scenario development method

When carried out properly, scenarios simplify the avalanche of data into a limited number of possible states. Scenario development is not a way to predict the future; but it helps to understand how the future may unfold [1]. Developed scenarios should be plausible, internally consistent and compelling. Dependencies between trends, forces, and key forces need to be considered. A trend is something that has an impact and will happen with great certainty. A force has an impact as well, but its outcome is more uncertain than a trend. Finally, a key force has a large impact, but its outcome is very uncertain. See Fig. 1. Two or three key forces form the basis of a scenario.

The objective of the scenario development exercise is: *To develop scenarios that help determine for the Netherlands the role of the gas distribution infrastructure in the energy system in 2050 and its corresponding functions.*

To obtain scenarios, some authors suggest adopting a general step-wise approach ([1], [2]). We have used this approach with a few adaptations. Our approach can be found in Fig. 2. The first step is to define the objective and scope. These were mentioned in the previous paragraph. Next we carried out a literature survey to identify trends, forces, and key forces. Consequently, our scenarios are based on existing scenarios instead of building them from scratch, as suggested by Schoemaker [1]. From these two key forces we derived four initial scenarios. An expert session was organized to verify the assumptions underlying the initial scenarios. The expert panel consisted of gas distribution experts from the Dutch Distribution Service Operators (DSOs), Kiwa Technology, Delft University of Technology and the University of Twente. Once consensus was reached on the initial scenarios, the forces were further quantified. For this quantification we used the report written by CE Delft [3]. Finally the scenarios were described in more detail. The most important results are described in section 4.

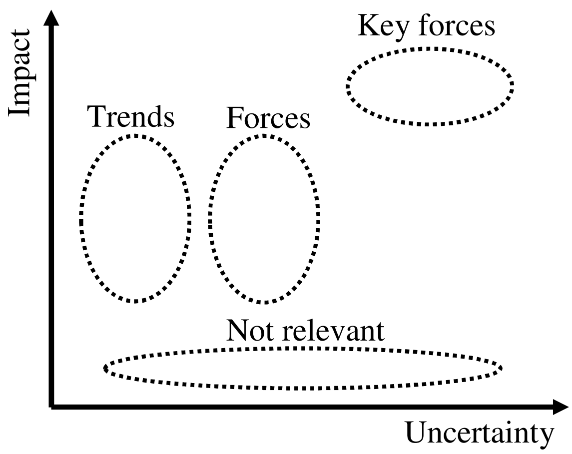

Fig. 1. Schematic representation of trends, forces and key-forces according to their degree of impact and uncertainty.

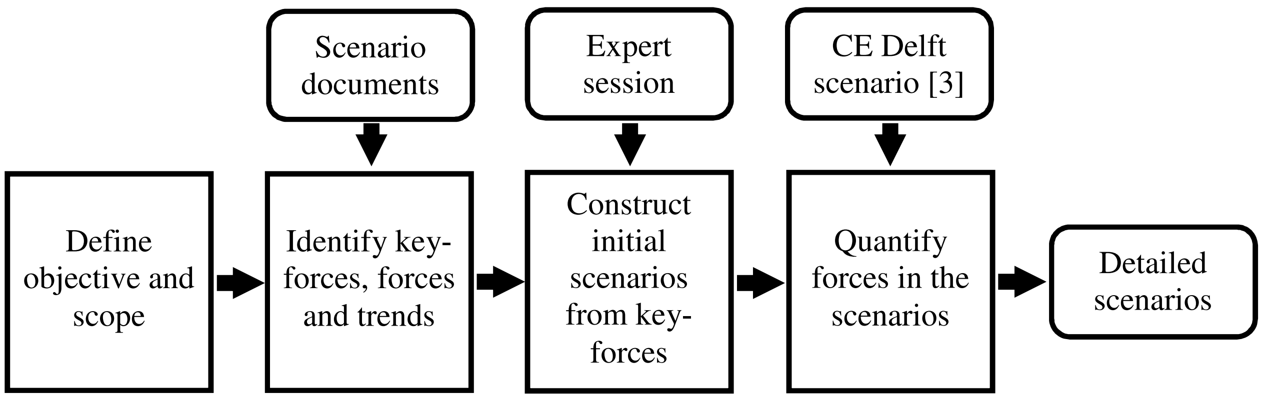

Fig. 2. Schematic representation of the steps followed in the research approach to obtain detailed scenarios.

3. What are the key forces, forces and trends?

As mentioned in section 2 our objective is to find the role of the gas distribution infrastructure in the Dutch energy system in 2050 and its corresponding functions. In the second step of the scenario development method, the key forces, forces and trends are derived. Fig. 3 summarizes the key forces, forces and trends that were derived. They are described in more detail in subsections 3.1 – 3.3.

3.1. Key forces

The *perceived energy resource scarcity* and the *willingness and ability to reduce GHG emissions* were chosen as key forces. To come to these key forces we have performed a literature survey. Four existing scenarios were used, although more scenarios have been examined. The used scenarios are studies performed by Shell [4], CE Delft [3], the United Kingdom Energy Networks Association (ENA) [5], and the Massachusetts Institute of Technology (MIT) [6]. Below these scenario studies are briefly described.

- In the study done by Shell [4], two global scenarios “Scramble” and “Blueprint” are described. The key forces in this study are the ability of the world to find effective answers to challenges such as global warming, resource scarcity, and population growth.
- In the CE Delft scenarios [3], the focus is on the Dutch energy infrastructure. Boundary condition in each scenario is a 90% reduction of CO_2 emissions in comparison to 2008. The described scenarios differ from each other in the technologies used to meet the projected energy demand.
- The ENA has developed scenarios [5] that focus on the British gas Sector. The key forces are further development and commercialization of carbon capture and storage (CCS) and electricity and heat storage technologies. The scenarios are based on the 2050 pathways analysis [7] of the UK Department of Energy and Climate Change. As with the CE Delft Scenario, the ENA scenarios take the strong reduction in GHG emission as a boundary condition as well.
- The MIT scenario study [6] examines the role of natural gas in the United States in a carbon constrained world with a time horizon out to mid-century. The key force is the extent and nature of GHG mitigation measures that will be adopted by the US and other countries.

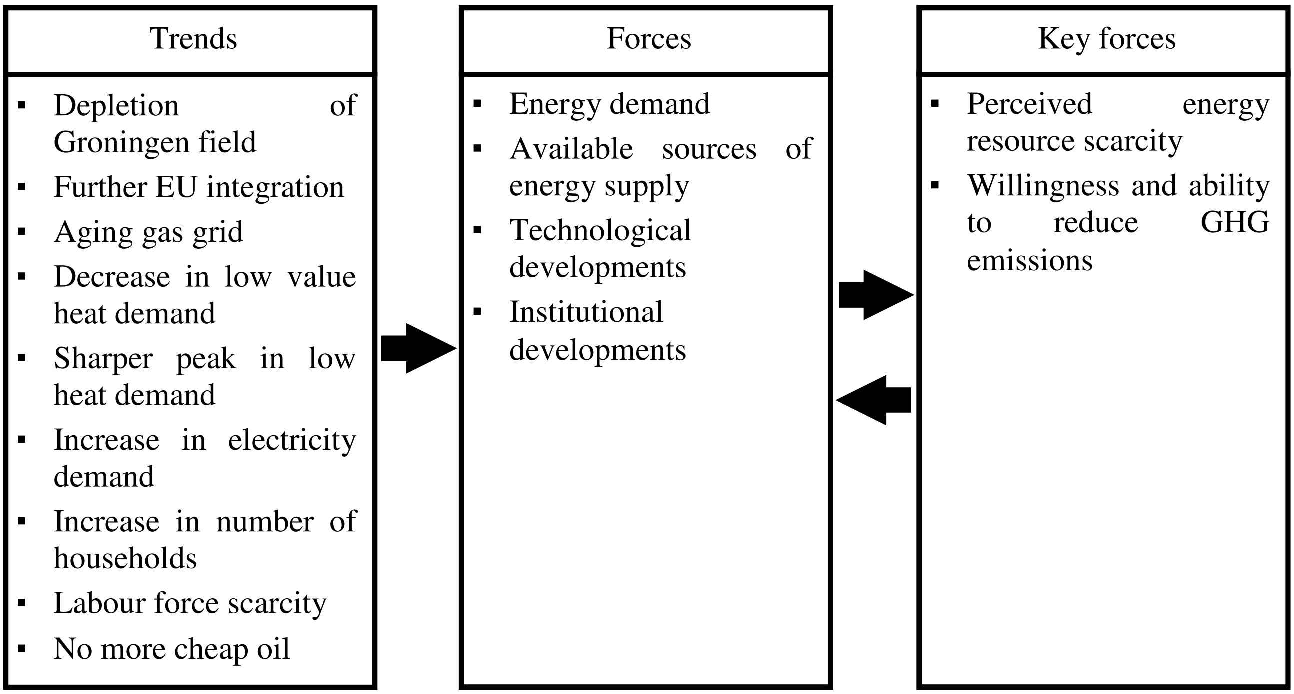

Fig. 3. Trends, forces and key forces, and their interrelations

In the Shell report one of the key forces is whether the world can find an effective answer to resource scarcity. When energy resources are perceived to be scarce, security of energy supply will be more of an issue. Energy conservation measures will become a logical response, in combination with increased local production from wind power, solar power and biomethane. This biomethane will be injected and distributed by the gas distribution infrastructure. Conversely, in a world with abundant fossil fuels, renewable energy projects will be economically less attractive and energy conservation measures will be less urgent.

Both Shell and MIT scenarios pinpoint the ability to find effective answers to reduce GHG emissions as a key force. This in contrast to the CE Delft and ENA scenarios where the mitigation of GHG emissions is taken as boundary condition. A strict GHG regime may mean that local combustion of natural gas is no longer allowed, and consequently the gas distribution infrastructure becomes obsolete in some parts of the country. Also the distribution system has to facilitate the injection and distribution of biomethane or biogas. Under a less strict regime, local combustion of gas will still be allowed; and therefore, the gas distribution infrastructure will face less rigorous changes.

In conclusion, the *perceived energy resource scarcity* and the *willingness and ability to reduce GHG emissions* have a large impact on the gas distribution infrastructure, while at the same time there exists uncertainty about their outcome. Therefore these factors are taken as the key forces. As such, they will form the basis of the scenarios.

3.2. Forces

Energy demand, *available sources of energy supply*, *technological developments* and *institutional developments* were chosen as forces. The forces are affected by trends and in turn affect the key forces. In this section the forces are described into more detail. Furthermore, it is described how they affect the key-forces and the future gas distribution system.

The *energy demand* is subdivided into four types of demand: (1) low value heat, which is the energy required for space heating and hot water supply and contributes to 35% of the total current domestic energy demand; (2) high value heat, which is mostly used in industry and contributes to 30%; (3) mobility, which is the energy demand for passenger and freight transport by road, rail and water and contributes to 10%; and (4) lighting and appliances which contributes 25% to the total energy demand. The energy demand determines whether the gas grid needs to be upgraded, remain as it is, or be decommissioned. In the detailed description for each scenario the demand is given. The energy demands for each scenario are derived from the CE Delft report [3].

The energy demand will have to be met by the *available sources of energy supply*. We divided the available energy sources in two dimensions. The first dimension is its origin: local/ regional; national/European Union (EU); and non-EU. The second dimension is the type of energy resource: renewable energy; nuclear energy; and fossil energy. The key forces will play a significant role in the energy mix. To give an example: when we want to secure the energy supply due to the *perceived energy resource scarcity*, this will lead to an increased use of local energy sources. With no scarcity, the energy supply mix will be determined by the worldwide market and consequently the share of non-EU resources will be higher. Apart from this, other factors affect the energy mix as well. For instance, for renewable energy, the availability of biomass plays an important role. The future gas grid will be affected by the eventual energy mix. An energy mix with a minor role for gas might lead to the abandonment of a great part of the gas distribution grid.

Technological developments will impact both the future role of the gas, as well as the gas distribution infrastructure. We examine three categories of the most important techniques: Firstly, for bridging longer periods, when supply of renewable energy coming from wind or solar for example is too high or too low, long term storage will be needed. We assume that the technology and ability to store electricity on a large scale will not become economically viable. Hence, the storage of gas remains significantly cheaper than the storage of electricity. It is, therefore, argued that in case of an electricity surplus from solar PVs and windmills, the surplus energy will be converted to hydrogen or methane and subsequently injected into the gas grid [8]. The required technology – hydrolysis for the production of hydrogen from water, and methanation by means of the Sabatier process for the conversion of hydrogen into methane – are assumed to have matured by that time. The renewable methane can then be supplied to power producers via the existing gas system and storage sites. Secondly, we assume an increase in the penetration of (micro-)CHPs, which simultaneously produce heat and power in an individual household or small commercial building. Thirdly, in view of the associated costs, we assume that CCS will only play a role when there is a willingness to reduce GHG emissions, and there is a large share of electricity production from fossil energy and/or large industry using fossil energy.

The fourth force is the *institutional developments*. We define institutions as "the rule of the game" [8]. How the energy system looks and works depends for a large part on the rules we collectively agree on. This pertains both to the degree of government involvement as well as to the level at which governments are involved, whether it is a local, national or supranational entity. For instance, if energy resource scarcity is perceived to be high, then this will be reflected by the institutions. Local self-sufficiency and integration between gas and electricity supply systems will probably be promoted with a clear role for local authorities. Furthermore, GHG reduction efforts will probably go hand in hand with new restrictions and/or incentives both on national and on EU levels.

3.3. Trends

In Fig. 3, nine trends are listed. In this section we will discuss three of them.

Due to the *depletion of the Groningen field*[1] and other domestic gas fields, domestic natural gas production will decline, and the Netherlands will become increasingly dependent on imported natural gas.

The *gas grid is ageing* and parts of the current gas grid and many components are about approaching their design lifetime. Replacement or renovations of the gas distribution system will require huge investments in the near future and important decisions about the design of these systems.

For reasons of cost and availability there will be *no more cheap oil in 2050*, and oil will be replaced by renewables, natural gas, coal or nuclear energy [10].

4. Scenarios

The key forces, forces and trends that were pinpointed have been used to construct four scenarios. For each scenario, an extreme of both key forces is taken, with the variable low or high. In the scenarios with a low *willingness and ability to reduce GHG emissions*, we are only to a limited extent able to cut carbon emissions. While in the scenarios with a high *willingness and ability to reduce GHG emissions*, we are successful in this attempt and strict regulations exist regarding the combustion of fossil fuels, and incentives are in place to stimulate the use of carbon neutral renewable energies. In the scenarios with a high *perceived energy resource scarcity*, availability of energy resources may be limited due to political, geological, technical or economic reasons. In the scenarios with a low *perceived energy resource scarcity*, resources are perceived to be plentiful available. The derived scenarios are summarized in Table 1. Below a more detailed description of each scenario is given.

Scenario 1: Business as usual

This scenario is closest to the current situation. The implementation of GHG measures stalls. Energy resources and especially gas are not seen as scarce. Russian gas, possibly European shale gas plus LNG, have replaced domestic natural gas. Local combustion of gas is still common

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[1] The Groningen field is the largest gas field in the Netherlands. Of the initial 2800 billion m^3 of natural gas, only 1000 billion m^3 remains as of 2010.

practice. The overall energy demand and more specific gas demand in this scenario is higher than the demand in 2008. Use of the gas distribution infrastructure is comparable to the present use.

Scenario 2: Carbon constraints

Reduction of GHG emissions compared to 2008 is a boundary condition in this scenario. As a consequence, combustion of natural gas is prohibited at a household level. Natural gas networks for households are substituted by electricity and heat networks. Domestic heat demand will be largely satisfied by heat pumps or centralized heating installations in combination with local heat grids. Only in areas where there is sufficient production of biogas and biomethane does the gas distribution grid remain in use. To minimize quality conversion costs, the gas standards in these grids will be tailored to regular biogas quality. The challenge will be to match the relatively constant supply of renewable gas to the fluctuating gas demand. The national gas transportation system still has a significant role though: transporting natural gas to large gas-fired power plants to produce electricity. The CO_2 released in the electricity production process is stored with CCS technology. Since there is no perceived energy resource scarcity, the gas used to fire the power plants is allowed to be transported from non-EU countries by pipelines. Besides natural gas, coal (also in combination with CCS) and nuclear energy have a significant share in the electricity production. Finally, renewable energy has a significant share in the energy mix. The total energy demand in this scenario is lower than in 2008 and the gas demand is about half that of 2008.

Scenario 3: Tight market

There is a perceived energy scarcity but no drive to reduce GHG emissions. Therefore, resources are diversified to be less dependent on one source of energy. Local renewable energy (among which also renewable gases, such as biomethane, biogas, synthetic natural gas (SNG), hydrogen and renewable methane) and energy conservation measures are seen as important and a means to increase security of supply. Due to the high share of renewable electrical energy, such as wind and solar, the fluctuation in these energy resources requires energy storage to bridge periods of shortage. As a consequence, the gas system will provide flexibility to balance demand and supply. The gas distribution infrastructure should facilitate both the distribution of fossil gases and injection and distribution of renewable gases. This could result in the subdivision of the distribution grid in different quality regions, each with its own specific gas quality. The energy demand in this scenario is the same as in the *carbon constraints* scenario.

Scenario 4: Renewable self-sufficiency

Reduction of GHG emission is a boundary condition in this scenario. It is, therefore, prohibited to combust natural gas at household level. Consequently, the role of the gas distribution grid is minimal, and natural gas is substituted by electricity and heat networks. Only in areas where there is sufficient production of biomethane and biogas, the gas distribution grid is still in use. To minimize quality conversion costs, the gas standard in these grids will be tailored to biogas quality. At a central level, gas can still be combusted in power plants in combination with CCS. Due to the perceived scarcity of energy resources, natural gas from non-EU countries will not be imported by pipeline. Instead, foreign/non-EU gas will be imported as liquefied natural gas (LNG) in order not to be too dependent on one supplier. However, preferably, all natural gas will be supplied by domestic or EU suppliers. Renewable energy plays an important role and energy conservation measures are seen as important and a means to decrease dependency. The largest share in the energy supply mix comes from renewable energy and especially biomass. Due to the high share of wind and solar, the balancing of supply and demand becomes challenging. The gas system, both transport and distribution, is used to balance supply and demand. Due to the fact that energy is perceived as scarce and GHG emissions need to be reduced, the energy demand is the lowest of all scenarios and gas demand is about half that of 2008. The share of biogas in this scenario is twice that of the *Tight market* and *Carbon constraints* scenarios.

Table 1. Scenarios per degree of willingness and ability to reduce GHG emissions and perceived scarcity of energy resources.

		Willingness and ability to reduce GHG emissions	
		Low	High
Perceived scarcity of energy resources	Low	**Business as usual** ▪ Energy is considered a commodity ▪ Natural gas and coal are main resources of energy supply ▪ Local combustion of natural gas and fossil fuel is allowed *Gas distribution system* ▪ Distributes different types of (foreign) natural gas and, to a very limited extent, biomethane	**Carbon constraints** ▪ Energy is considered a commodity ▪ Natural gas, coal and nuclear are main resources of energy supply ▪ Fossil fuels are converted to electricity in large scale power plants with carbon capture storage ▪ Biomethane is used for CO_2 emission reduction ▪ No local combustion of natural gas and fossil fuel is allowed *Gas distribution system* ▪ Only for biomethane/biogas
	High	**Tight market** ▪ Diversification of sources (liquefied natural gas and maximal local renewable energy) to secure energy supply ▪ Biomethane and biogas are stimulated to reduce resource dependency ▪ Local combustion of natural gas and fossil fuel is allowed *Gas distribution system* ▪ Accommodates different types of (foreign natural) gas, biomethane, biogas, renewable methane and hydrogen ▪ Used to balance electricity distribution system	**Renewable self-sufficiency** ▪ Biomass, wind , and solar are main sources of supply ▪ Policy focused on security of supply by maximum use of local renewable energy sources ▪ No local combustion of natural gas and fossil fuel is allowed *Gas distribution system* ▪ Only for biomethane, biogas, renewable methane and hydrogen ▪ Used to balance fluctuating supply from windmills and solar energy

For the detailed scenarios we refer to [11]. Here the demand per scenario per demand type are quantified, as well as the energy mix in each scenario. The values are based on values found in literature [3]. Also for each energy mix the gas mix is identified.

5. Impact of scenarios on the gas distribution infrastructure

With the scenarios at our disposal, in the next research step we want to assess the impact of the scenarios on the Dutch gas distribution system. If one of the scenarios becomes reality, what will the gas distribution system look like? What are the required investments and divestments?

Section 5.1 describes how the research will be performed, section 5.2 shows some preliminary results and section 5.3 describes what further information we want to derive from the research.

5.1. Method

It is not worthwhile to analyse the whole Netherlands; an analysis on three regions, that are a cross selection of the Netherlands, will also be representative . This selection of representative regions is based on (1) biomass availability, which determines the potential volume of biogas and biomethane production; and (2) population density, which determines the size of the gas demand. This is shown in Fig. 4, having:

- A rural region (Noord-Drenthe), which is typified by a high availability of biomass and a low population density.
- An intermediate region (Arnhem/Nijmegen), which has a medium availability of biomass and a medium population density.
- An urban region (The Hague), which has a low availability of biomass and a high population density.

The findings for the three regions can be used for other regions as well, and usually will lay somewhere in between the analysed regions

Analysis will partly be done by means of a tool developed for our research, see [12], and partly by calculations by hand. The tool consists of a multi-objective optimization model that, given a certain spatial distribution of biomass and gas grid with gas demand, generates biogas supply chains for the use of the biomass. It allocates and sizes, among others, digester installations, upgrading plants, biogas pipelines, biomethane pipelines, and gas storages. The optimization objectives of the tool are yearly CO_2 reduction (achieved by the replacement of natural gas by biomethane or biogas), yearly local energy produced from the available biomass, and the Net Present Value of the configuration.

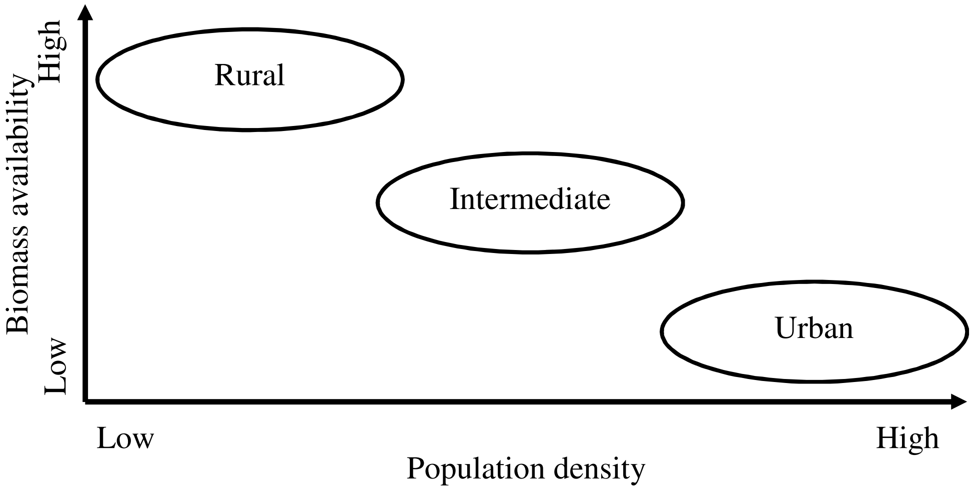

Fig. 4. The three regions that form a cross selection of the Netherlands

The ambitions for CO_2 reduction and local energy production in the scenarios are used as exogenous input to the tool. It depends on the chosen scenario what the optimisation goal(s) will be. In case of the *Business as usual* scenario, only the cost will be optimised, since there is no energy scarcity and no need to reduce GHG emissions. In the *Carbon constraints* scenario there is a drive to reduce GHG emissions and, therefore, the CO_2 reduction ambition will be important. In the *Tight market* scenario, there is no need to reduce GHG emissions, but there is a perceived energy resource scarcity and, thus, the yearly local energy production objective becomes important. Finally, in the *Renewable self-sufficiency* scenario both the CO_2 reduction and the yearly energy production objective are of importance. Furthermore, the existing gas grid in each of the 3 regions will be taken as a starting point. The distribution grid will be taken into account. To each of these grids, gas consumers are connected. The gas demand of these consumers in 2050 is derived from the values found for the gas demand in the scenarios. In the next section the layouts for the *Carbon*

Constraints and *Tight Market* scenarios for the intermediate region will be determined by the multi-objective optimization tool.

5.2. Possible future layouts for the intermediate region

In this section we will describe the layout of the gas grid and the accompanying biogas infrastructure for the intermediate region, for the *Carbon Constraints* and *Tight Market* scenario. The intermediate region is characterized by medium population density and a medium biomass availability. As intermediate region we take the cities of Arnhem and Nijmegen and the surrounding more rural municipalities. In Fig. 5. the high pressure distribution gas grid (operated at pressures ranging from 1 to 8 bar) of this region is shown, including farmers that are located in this region. The farmers have a certain amount of biomass available and it can be used to produce biogas and biomethane. Furthermore, gas consumers are connected to the gas distribution grid, these are also shown in Fig. 5. In reality the grid consists of more gas consumers than shown in this figure, however we have simplified the grid by taking the district stations that supply gas to the low pressure distribution grid as the gas consumers. District stations reduce the gas pressure coming from the high pressure distribution grid and feed it to the low pressure distribution grid (operated at pressure ranging from 30 to 200 mbar). The aggregated gas demand of the consumers in the low pressure distribution grids are assigned to the district stations, and are represented as gas consumers in Fig 5.

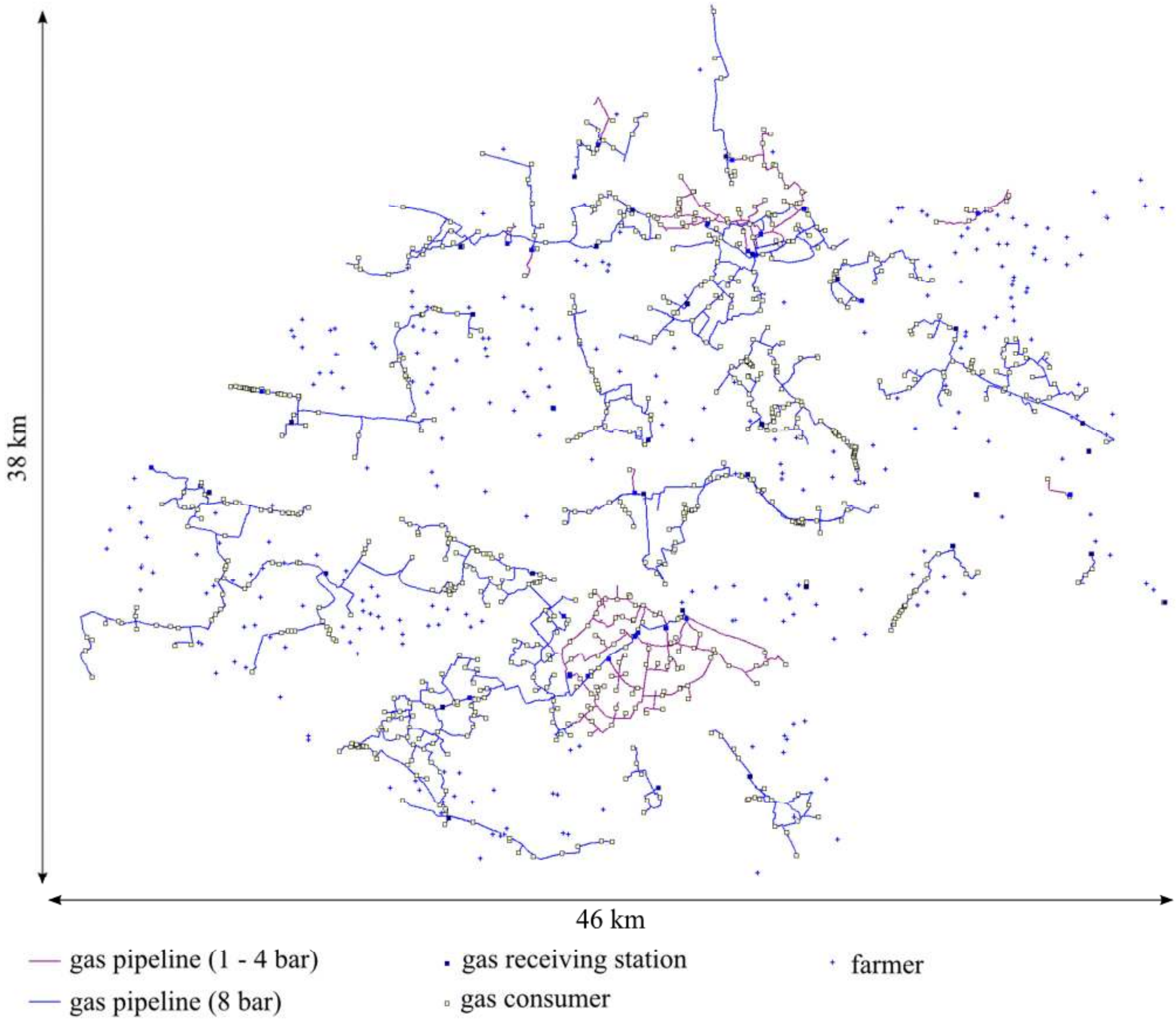

Fig. 5. The current layout of the high pressure distribution grid of the region Arnhem/Nijmegen. Plus surrounding farmers whose biomass might potentially be used.

The configuration shown in Fig. 5. is taken as the starting point for the multi-objective optimization tool, and is used to come to the possible future layouts.

In the *Carbon Constraints* scenario there is no perceived scarcity of energy resources, but there is a strong drive to reduce CO_2 emissions. Hence, the national government provides subsidy on the production of biogas (in this scenario the gas quality in the gas distribution grid is adjusted to biogas), therefore there is an incentive for the farmers shown in Fig. 5. to produce biogas. By means of the multi-objective optimization tool we generate potential future layouts maximizing CO_2 emission reduction.

Fig. 6. shows the biogas supply chain for the intermediate region in the *Carbon Constraints* scenario, that maximizes CO_2 emission reduction. It is characterized by local digestion of biomass, and production of biogas. There are some biomass movements that transport biomass from a farmer to a central, larger, digester. Furthermore, since the gas demand during the year is not always sufficient to consume all biogas produced, gas compressors are added to compress the gas and inject it to a higher grid. Ultimately to the national 40 bar grid. Where we assume that gas demand will always be sufficient.

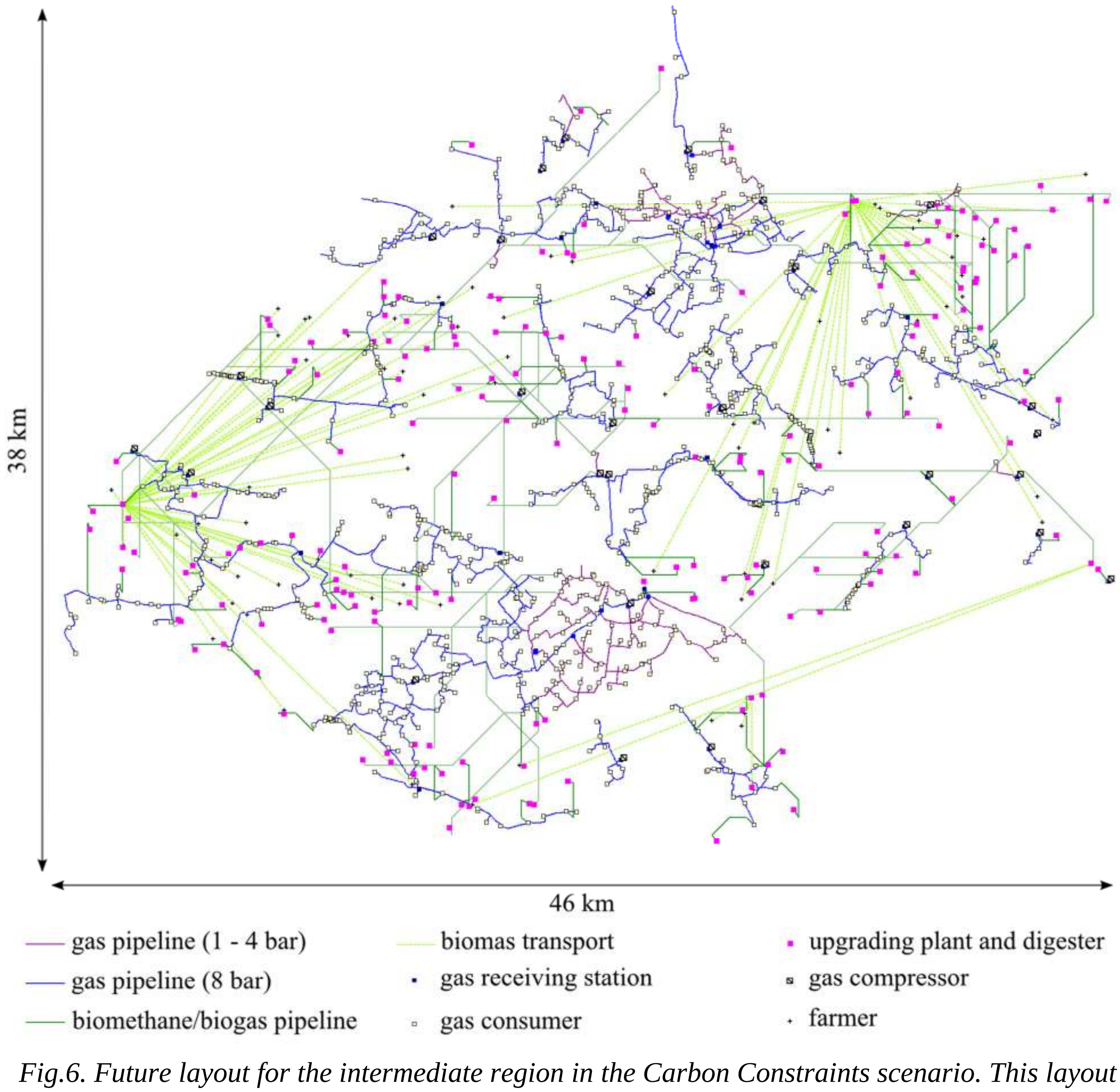

Fig.6. Future layout for the intermediate region in the Carbon Constraints scenario. This layout gives the maximum CO_2 reduction while still having a positive NPV.

In the *Tight Market* scenario there is a perceived energy scarcity, therefore there is a strong drive to use locally available biomass for the production of biomethane. There are no incentives to reduce CO_2 emissions, and hence the gas distribution is still used to transport natural gas. Therefore, the biogas has to be upgraded to natural gas quality, resulting in extra costs for the biomethane. By means of the multi-objective optimization tool we generated potential future layouts, maximizing energy production.

Fig. 7. shows the layout derived for the *Tight Market* scenario. Compared to the layout shown in Fig. 6. there is hardly any local digestion of biomass, and the largest part of the biomass is transported by truck to one of the central digestion locations. Similar to the other layout , also in this case the gas demand from the gas consumers is not always sufficient to consume all produced biomethane. In those cases the biomethane is compressed and injected in a higher grid. Again, the national 40 bar grid is assumed to have sufficient gas demand.

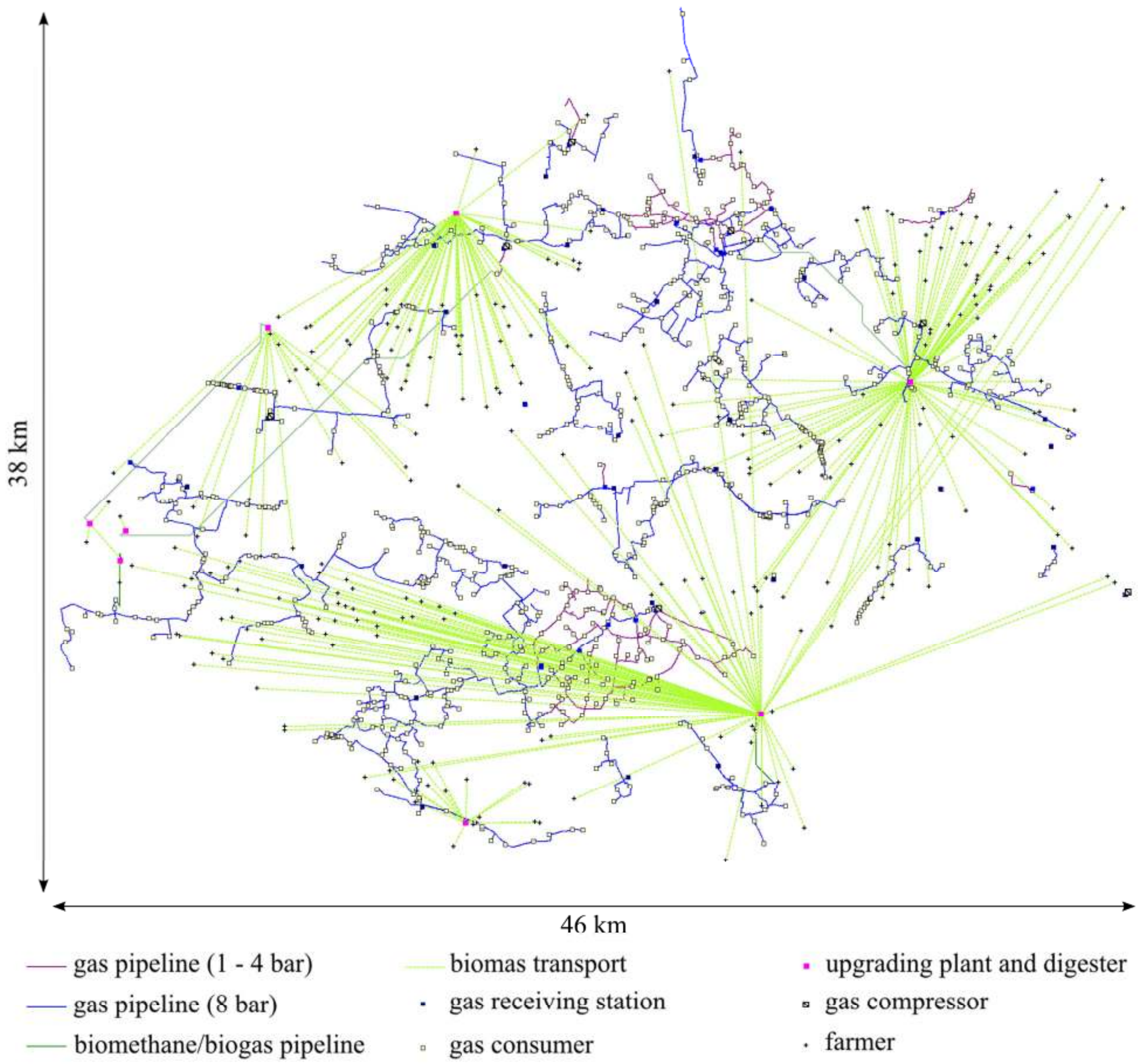

Fig.7. Future layout for the intermediate region in the Tight Market scenario. This layout gives the maximum biomethane production while still having a positive NPV.

Despite that in both the *Carbon Constraints* scenario and the *Tight Market* scenario there is a strong drive to produce biogas/biomethane, the eventual layouts differ. And therefore, the actual investments differ for both scenarios. For instance, in the *Carbon Constraints* scenario 50 million € has to be invested in gas pipelines, while in the *Tight Market* scenario only 7 million € has to be invested. And where in the *Carbon Constraints* scenario investment need to be made in a lot of local digesters, in the Tight Market scenario, we should invest in four large central digester installations.

However, it has to be kept in mind that the found layouts are dependent on the values chosen for investment and operational cost for the different components in the biogas supply chain. It should be investigated how sensitive these optimal layouts are to changes in those values.

5.3. Further research

The previous section showed how, by means of the multi-objective optimization tool, we will determine the future layouts for the different regions. In this section we want to elaborate a bit on further research to be done on the impact of the future scenarios on the gas distribution grid.

As shown in section 5.2, on the biomethane and biogas side we want to know what the ideal biomethane infrastructure looks like. Are there robust configurations that come back in each scenario? What is the best way to deal with imbalances between biomethane supply and gas demand (for instance compressing the surplus biomethane to a higher grid, or temporary storage of biomethane)? Is the found configuration for biomethane, if it exists, the same for each scenario, or are their similarities that can be identified? And what are the associated cost of the established infrastructure, for the biogas producer, for the DSO, and for the society as a whole?

It is worthwhile to see what the layout of the gas distribution system and its characteristics will be in 2050 for each scenario. It might, however, be even more worthwhile to know, which investments will pay off in more than one scenario. This might not be the best solution in any of the scenarios, but performs well overall. Therefore, we will also investigate what the robust investments are. To come to these robust investments a method will be used that is inspired by the concept of robust design (see for instance [13]). In robust design, when designing a product, two potential designs might have the same performance. However, one of these designs might be less sensitive to uncontrollable variations. This design is more robust. For our scenario analysis we want to come to a robust design for the future gas infrastructure. A design that not only performs well in one scenario but also, when the future does not exactly unfold like the scenario predicted, in another scenario.

In conclusion, in follow-up research we want to know what the differences and similarities are among the scenarios when looking at investments and divestments. And secondly, we will assess the robust investments, which may not be optimal in any of the scenarios, but will pay off in more than one scenario.

6. Conclusions

We aimed at developing scenarios that help determine for the Netherlands the role of the gas distribution grid in the energy system in 2050, and finding the corresponding future layouts of the gas grid.

Willingness and ability to reduce GHG emissions and *perceived scarcity of energy resources* were identified as key forces. From the key forces, four scenarios were derived that differ from those found in literature: The 80 to 90 percent CO_2 emission reduction is not a boundary condition as is the case in other scenario studies, for instance the scenarios developed by CE Delft [3], ENA [5], Forschungs Verbund Erneuerbare Energien [14], and the European Gas Advocacy Forum [15]. The scenarios developed in this paper have a strong focus on the gas distribution grid. In other scenarios, if mentioned at all, it is only mentioned briefly as in the CE Delft study [3] and the European Gas Advocacy Forum study [15]. Finally, our scenarios focus on the Dutch situation, which is different from the aggregate European [16], United Kingdom [5] and German situations [14]. Therefore our scenarios are of more use for the Dutch DSOs.

In the last part of the paper we showed what the future layout of the gas distribution grid and accompanying biogas infrastructure might look like, in the intermediate region, for two future scenarios. Furthermore, the follow-up research, detailed in the last part of the paper, will give an idea of the typical investments for each scenario, and also what the robust investments are that pay-off in more than one scenario. These robust investments will help the DSOs in dealing with their investment dilemma.

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