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Technology and Policy Aspects

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Smart Gas Grids: Technology and Policy Aspects

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Nomenclature

κ	The number of independent loops in the network
CHP	Combined heat and power
$CHPC$	Combined heat, power and cooling
D	The internal diameter of the pipe
d	The relative density of gas compared to air
DSO	Distribution system operator
f	Friction factor
g	Gravitational acceleration
$G - gas$	Groningen gas
GCV	Gross calorific value
GRS	Gas receiving stations
h	The height difference between the pipe entrance and pipe exit
$H - gas$	High calorific gas
HTL	High pressure transmission lines
k	The number of independent loops in the network
K_k	The pipe constant for pipe k
L	The length of the pipe
l	The iteration number
$L - gas$	Low calorific gas
L_i	The load at node i
LNG	Liquefied natural gas
m	The number of branches in the network
$M\&R$	Metering and regulating
n_1	The number of load nodes in the network
p_1	The absolute pressure at pipe entrance

p_2	The absolute pressure at pipe exit
p_i	The absolute pressure at node i
p_n	The standard pressure
p_{av}	The flow average pressure
Q_n	The volume flow rate at standard conditions
R_{air}	The gas constant for air
RTL	Regional transmission lines
T	The absolute temperature
T_n	The standard temperature
TSO	Transmission system operator
Z	The compressibility factor

1 Introduction

The term *smart grid* is typically associated with power systems, but it can also be applied to gas and heat networks. There is no consensus on the definition of smart (gas) grids in the literature. We use the description provided in [27]: *the smart gas grid concept is based on maximizing the efficiency of overall energy usage and taking full advantage of the flexibility and all the opportunities that gas and the gas grid can offer.*

In this report we present the results of a six-months project on technology and policy aspects of smart gas grids, performed between October 2014 and April 2015. The project has led to a successful *Energy System Integration: planning, operations, and societal embedding* (ESI-pose) application in 2015, increasing the degree of collaboration between the faculty of Technology, Policy and Management (TPM) and Numerical Analysis section of Electrical Engineering, Mathematics and Computer Science (EEMSC) faculty.

The project was comprised of two parts:

- interviews with experts from the TU Delft,
- literature study.

The interviews with the experts from both faculties were held in order to provide an overview of relevant research areas related to smart gas grids. Due to privacy constraints the overview is left out from the publicly available version of the report.

The results of the literature study are presented in Chapter 2, 3, and 4. The policy aspects are described in the former two chapters, while the technology aspects are discussed in the latter one. More precisely, Chapter 2 provides the background information on natural gas and its use in the Netherlands. It describes the gas quality, demand, storage, transmission, and distribution networks. Chapter 3 discusses the possible use of the gases produced from biomass by thermodynamical conversion and anaerobic digestion. For instance, under certain regulations these gases can be injected in the distribution part of the natural gas grid. Chapter 4, fully based on [34], introduces the physical and mathematical fundamentals for the steady-state simulation of gas networks. It provides the general equation describing the steady state gas flow, non-linear systems derived from Kirchhoff's laws and several techniques based on the Newton method which are commonly used for solving these non-linear equations. Furthermore, Chapter 5 gives a general idea of the collaboration of Numerical Analysis section with Energy and Industry, and Economics of Technology and Innovation sections of the TPM department. Chapter 6 indicates several possible research questions. The questions are based on the literature study as well as the interviews with the experts.

2 Natural Gas

Natural gas is the most well-known methane-containing gas. Depending on its origin, natural gas can differ in presence of chemical elements and composition, and therefore, for instance, the amount of energy produced by combustion. The quality of natural gas is typically described by its Wobbe index or calorific value.

Definition 1 *The gross calorific value (GCV) is the amount of heat released by the complete combustion of a specified quantity of gas under the condition that the products of the combustion are brought back to the initial temperature*[1].

Definition 2 *The Wobbe Index is calculated as follows*

$$Wobbe\ index = \frac{GCV}{\sqrt{d}}, \tag{1}$$

where d is the relative density of gas compared to air.

Depending on its calorific value, natural gas is divided into two groups:

- high calorific natural gas (H-gas), and
- low calorific natural gas (L-gas).

The modern history of natural gas in Europe began in 1959 with the discovery of an extensive natural gas field in the north-eastern part of the Netherlands near the village of Slochteren in the province of Groningen. A few years later, natural gas was discovered in the UK sector of the Northern Sea, followed by the Norwegian sector of the Northern Sea in 1979 [6].

During the late 20th century, the gas industry in Europe rapidly developed. Today it accounts for more than 20% of European energy demand [33]. Recently, however, the capacity and hence the production of gas fields in Groningen and North Sea begun to decline. As a result, only 38% of the gas used by the EU member states countries in 2007 was indigenous. The remainder was imported from different sources outside Europe: 24% was supplied from Russia, 14% - from Norway and more than 20% was imported from the Middle East, North Africa, Caribbean and other sources [46]. Approximately 16% of the imported gas is supplied as LNG (liquefied natural gas) [46], whereas the remaining part is transported through pipelines. The major import pipelines to the EU countries are:

- Green Stream (from Libya to Italy, 520 km, opened in 2004 [11])
- Langeled (from Norway to the UK, 1,166 km, opened in 2006 [6])
- Nord Stream (from Russia to Germany, 1,222 km, opened in 2011 [6])

Furthermore, Nabucco project has been announced to provide further natural gas supplies to the EU.

[1] Various conditions are used as a reference, i.e. the reference temperature varies from 0 °C in the Netherlands to 25 °C in Belgium.

2.1 Situation in the Netherlands

2.1.1 Quality

The gas discovered near Slochteren is called Groningen gas or G-gas. G-gas is a low calorific gas or L-gas with the gross calorific value of 35 MJ/m^3 and the Wobbe index equal to 44 MJ/m^3. It is composed of 82% methane, 14% nitrogen and minor quantities of higher hydrocarbons - butane, ethane, hexane and propane - along with oxygen and carbon dioxide [48].
In addition to Groningen field, there are several smaller natural gas fields in the Netherlands. Gas from the smaller fields is high calorific.

2.1.2 Demand

Approximately 48 billion cubic meters (bcm) of natural gas was consumed in the Netherlands in 2011 [18]. The gas was mainly utilized by the transformation sector (>30%). Residential and commercial/industrial sectors accounted for 22% and 20%, respectively.
There is a strong seasonal variation in gas demand. This is caused by the fact that almost all space heating and 60% of electricity is obtained by gas-fired generation. In fact, in 2010-2011 daily gas consumption varied between 88 million cubic meters (mcm) in the winter and 165 mcm in the summer [17].

2.1.3 International trade

The Netherlands is an exporter country, because it produces more gas than it uses domestically. However, it is expected to become an importer between 2020 and 2025, because the Dutch indigenous gas production is declining [18]. In 2011, the Netherlands exported approximately 55.8 bcm of natural gas to Germany (21.8 bcm), Belgium (10 bcm), Italy (8.7 bcm), France (7.4 bcm) and the United Kingdom (6.7 bcm). In the same year, 26 bcm of gas, originating mainly from Norway, the UK and Russia, was imported to the Netherlands [18].

2.1.4 Network

The high pressure transmission lines (HTL) with a pressure between 40 and 67 bar transport H-gas and G-gas across the country. The transmission network consists of approximately 6,000 km of pipes with an average diameter of one meter. The network is separated in two loosely coupled subnetworks with different quality regimes: H- and G-gas HTL [39]. The G-gas HTL grid transports gas that requires further distribution to residential and commercial consumers, while the H-gas HTL grid transports gas to large industrial customers and power generators. Both grids are presented in Figure 1. H-gas can enter the G-gas network, only if at a blending station its quality is adopted to that of G-gas by the addition of nitrogen.
Furthermore, the HTL grids are connected to the Dutch gas storage sites and used for

the transportation of imported and exported gas [43]. The Netherlands exports gas to Germany, Belgium, France, Italy and Switzerland [48], while the imported gas originates mainly from Russia, Norway and Algeria.

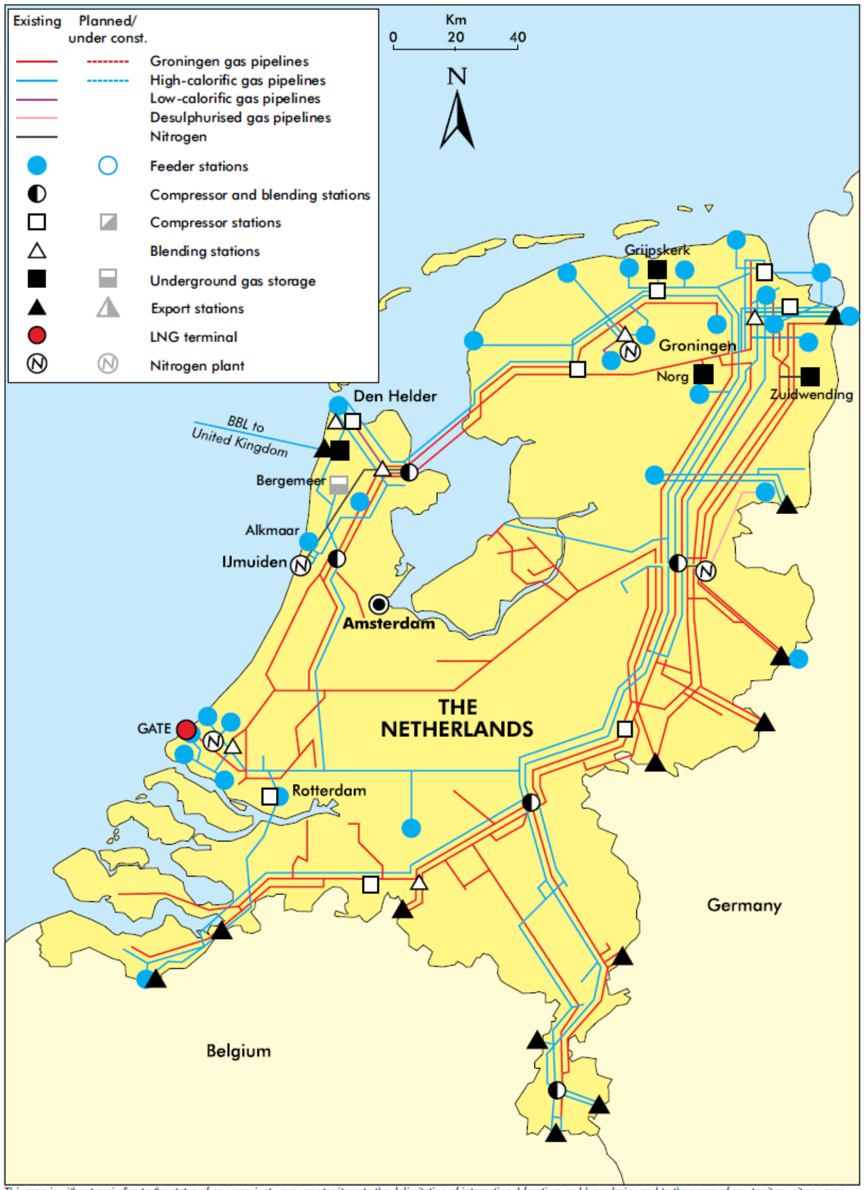

Figure 1: Natural gas transmission network.

The G-gas HTL network delivers the gas to metering and regulating (M&R) stations, that decrease the pressure to 7-40 bar and transfer gas to several regional transmission lines (RTL) grids. The RTL network is comprised of pipes with a total length of circa 6000 km and an average diameter of 25 cm [39]. It transports the gas further into the country to gas receiving stations (GRS) that reduce pressure to approximately 8 bar and supply the gas to the distribution network.

The distribution network with an approximate length of 127,000 km [14] consists of a low pressure distribution grid and a high pressure distribution grid. The high pressure distribution grid is used for the transportation over longer distances. It is connected to the low pressure distribution grid via supply stations, where the pressure is reduced to 100 or 30 mbar.
The low pressure distribution grid is directly connected to smaller industry and households. In fact, the distribution network is entirely composed of pipelines and supply stations [43]. The complete Dutch gas supply chain is schematically shown in Figure 2.

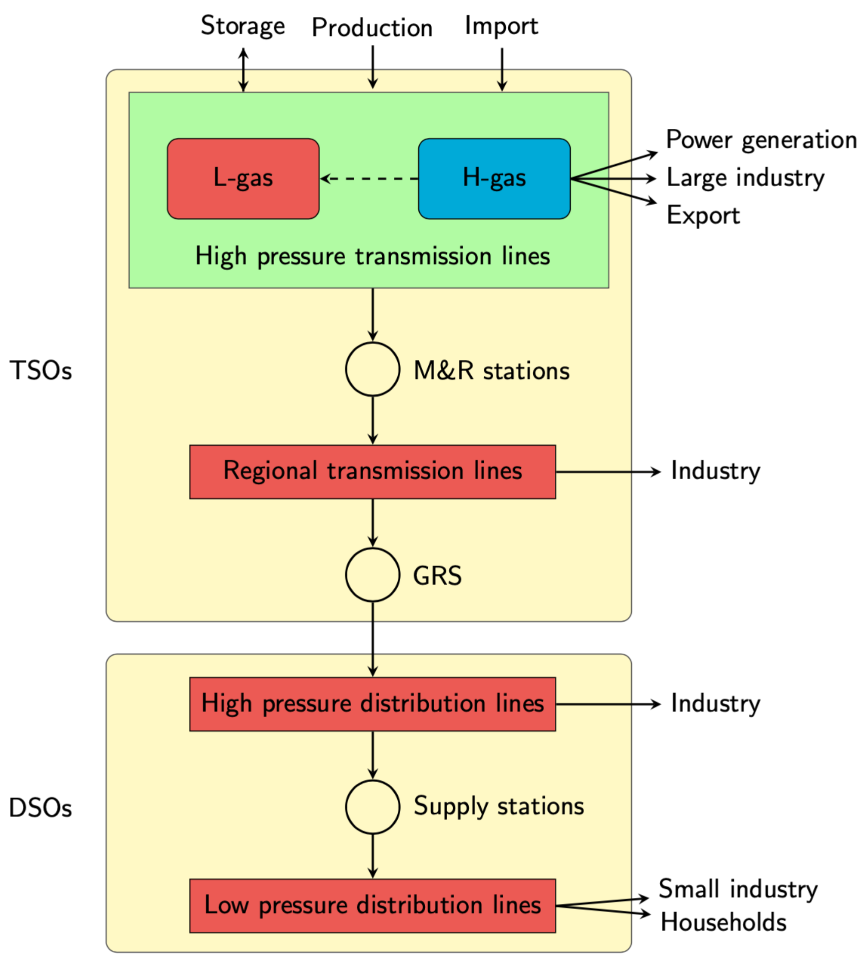

Figure 2: The Dutch gas network (based on [39, 43]). We distinguish between transmission system operators (TSOs) and distribution system operators (DSOs). M&R and GRS represent metering and regulating, and gas receiving stations, respectively.

The Dutch natural gas network is connected to four European countries (Germany, Belgium, Norway and the United Kingdom) via 25 interconnections. The lines interconnecting

Storage site	Working capacity[2] in mcm	Peak output in $\frac{\text{mcm}}{\text{day}}$[3]	Peak input in $\frac{\text{mcm}}{\text{day}}$[4]	CV
Norg	3000	51	30	L
Grijpskerk	1500	55	12	H
Alkmaar	500	36	3.6	L
Zuidwending	200	38	19	L

Table 1: Natural gas storage capacity in the Netherlands based on [17].

the Netherlands with Germany and Belgium allow gas transport in both directions. The connections to Norway are used only for import, while those to the United Kingdom are used only for export [18].

2.1.5 Storage

There are four underground natural gas storage facilities in the Netherlands (Table 1). They provide a total working capacity of 5.2 bcm. The reservoirs located in Norg, Grijpskerk and Alkmaar originated due to the depletion of gas fields, while in Zuidwending a cavern was adapted for gas storage. The facilities in Norg, Alkmaar and Zuidwending are used for the L-gas. H-gas is stored in the Grijpskerk reservoir.
Furthermore, ten coverns in Epe, Germany are connected to the Dutch transmission network. They account for 1.5 bcm of working capacity.

2.1.6 Network security

The annual number of leaks in the Dutch distribution network is approximately equal to 20 per 1,000 km [19]. From the technological point of view, the distribution system operators do not adopt any measures to improve the network security. In fact, their focus is on the increase of awareness of the importance of reparation activities among the employees. This general strategy originates from the fact that 80% of the leaks are caused by the human errors.
The security system of the transmission network is more sophisticated than that of the distribution network. This is caused by several factors. Firstly, the pressure in the transmission pipelines is significantly higher, hence, the consequences of a leak are more serious. Secondly, the transmission system was built decades after the construction of the distribution network. Therefore, it is technologically more advanced and allows better monitoring of the gas flow.

[2] Total gas storage minus cushion gas.
[3] The maximum rate at which the gas can be withdrawn from storage.
[4] The maximum rate at which the gas can be injected into storage.

2.1.7 Trends

There are several factors forcing innovation in the Dutch gas sector. A short overview of the trends in the Dutch gas system is provided below.

- It has already been mentioned that the Groningen gas field is in decline. Production of H-gas at smaller fields is also gradually declining [20, 43]. Therefore, the amount of imported natural gas to produce the so-called pseudo-G-gas is increasing. The conversion to pseudo-G-gas is required, because the gas imported from e.g. Russia, Algeria and Norway is high calorific, while the Dutch gas appliances are calibrated for the G-gas [43].

- It is also expected that over time the composition of gas available from Russia and Norway will change [20]. Different compositions can exert impact on network infrastructure and end-use equipment. For instance, higher fractions of CO_2 can lead to the so-called flame-lift[5] or even blow off[6] in domestic equipment.

- The frequency of the earthquakes due to the gas extraction is increasing. In order to ensure the safety and protect their properties, local people protest against further explotation of the Groningen field.

- The Dutch gas network is aging. Extensive renovation and replacement of many system components will be required in the near future [45].

- Due to the liberalization of the Dutch gas market, the government cannot continuously control the situation in the gas sector. Since the companies generally attempt to maximize their profit, this can stifle organized innovation and affect the trade with other countries.

- Non-conventional gases, such as biomethane (also known as green gas), are increasingly being injected into the Dutch natural gas network [20]. The New Gas Platform[7] aims to increase the share of biomethane in the natural gas network to 8 - 12% by 2020 and to a share of 15 - 20% by 2030 [43]. Moreover, the admixture of hydrogen to the gas network will be an attractive option in the future [48, 31]. Undoubtedly, the substantial injection of new gases into the gas network would require the introduction of additional safety regulations. However, according to [16], the distribution grid is able to transport sustainable gases under the condition that humidity is controlled.

- Due to the increasing democratization of energy production, a growing number of local communities attempt to create autonomous energy supply systems. This implies that some natural gas pipelines will be used for gases obtained from biomass.

[5] Flame lifts occur when the edges of flame are no longer attached to the burner.

[6] Flame blow off implies total disappearance of the flame. This can result in the disabling of the appliance or pouring of combustible mixture into the living space.

[7] The New Gas Platform is *an organization initiated by several Dutch ministries to promote green gas among parties in the Dutch society [43].*

- The use of natural gas reduces the noxious emissions compared with other fossil fuels. Contrary to coal and crude oil, by the combustion of natural gas the sulfur dioxide emissions are almost negligible, the levels of nitrous oxide and carbon dioxide emissions are significantly lower [29].

3 Biomass gasification and biogas

Biomass is organic matter that can be converted into energy. The integration of biomass in the existing energy systems of the EU member states is encouraged by the Renewable Energy Source Directive 2009/28/EC from 2009, which requires 20% share of the renewable energy sources in final energy consumption by 2020 [13]. Various technologies have been developed to utilize biomass for energy production. For example, biomass can be gasified using thermochemical conversion, whereby a solid fuel is transformed into a mixture of carbon mono- and dioxide, hydrogen, nitrogen, methane, water and small contaminants. The resulting combustible gaseous fuel can find flexible application by industries or home users [47].
Another possible way to utilize biomass is by converting it to biogas. Biogas is a generic term for gases produced either from natural decomposition process in landfill or by anaerobic digestion of organic matter such as energy crop, food waste and sewage sludge. The main components of biogas are methane (55-70%) and carbon dioxide (30-45%), but it also contains water, hydrogen sulfide and other trace gas components.
In the remaining part of this section, we discuss the applications of biogas and products of biomass gasification relevant to the smart gas grids technology.

3.1 Injection into natural gas network

Although the exact composition of raw biogas varies depending on its source, its calorific value is consistently much lower than that of natural gas. For this reason, biogas generally undergoes the process of upgrading prior to the injection into a gas network[8]. Upgrading to biomethane can be achieved by various techniques based on absorption, permeation or cryogenic upgrading in order to separate CO_2 from biogas.
Before feeding into a gas network, biogas is also purified. Purification is a physicochemical[9] or biological procedure required to eliminate undesirable contaminants such as hydrogen sulfide, ammonia and siloxanes. This is necessary to prevent corrosion, erosion, generation of hazardous emissions and other negative effects.

In [9] it is pointed out that there are no restrictions on the biogas injection to natural gas H, if it fulfills the following requirements:

[8] For stationary block heat and power plants dried and desulfurised biogas gas can be fed without upgrading.

[9] *Chemical absorption in aqueous solutions and absorption on solid absorbents, catalytic oxidation over activated carbons, and scrubbing with solvents or other liquid phases* [8].

- CH_4 content is at least 96% by volume;
- O_2 content is less than 0.5% by volume;
- H_2S content is at most $5mgNm^{-3}$;
- Water vapor dew point is below the average soil temperature of the region where the gas is supplied;
- Relative humidity is at most 60%.

However, when biogas is not completely compatible with the distributed natural gas, then the maximum feedable biogas rate is determined by the Wobbe index of the resulting mixture. For instance, in Denmark approximately 25% of biogas with CH_4 content of 90% may be used. Without upgrading and purification, up to 8% by volume is allowed to be mixed under the condition that the methane content is at least 60%.

Furthermore, mixing devices at the feed point should be driven continuously to ensure a homogeneous mixture in the downstream network. For safety reasons, large biogas injection plants are required to have odorization mechanisms, which are generally very expensive. To reduce the costs for relatively small plants, it is recommended to odorize natural gas a little further upstream to prevent odorization of biogas. Moreover, pressure and density must be adjusted before biogas is added to natural gas network [9].

3.2 Hydrogen production

Biomass gasification is one of the variety of ways to produce hydrogen.[10] The use of hydrogen perceived as a promising option for future energy systems, despite the undeveloped technology for end-use appliances and high production and transportation costs [48]. In fact, many disadvantages associated with the use of hydrogen can be avoided if the gas is added to natural gas network.

First of all, only limited adaption of end-use appliances is required when hydrogen is mixed with natural gas. Secondly, with little or no changes, existing natural gas pipelines can be used for storage and transportation of the gas mixture. Moreover, hydrogen may be used instead of nitrogen to 'water down' high calorific gas. Finally, partial substitution of natural gas by hydrogen reduces carbon dioxide emissions.

3.3 Combined heat and power generation

CHP, or co-generation, is the combined production of heat and electricity in one technological process. Although power generating efficiency of a CHP unit is circa 40%, its overall

[10] Other possibilities are, for example, electrolysis of water using solar, wind or geothermal energy, coal gasification and steam methane reforming [48].

efficiency can reach 90% [2, 9]. This can be achieved by using all excess heat from power generation for space heating, water heating or another process requiring thermal energy.
In general, CHP units are fuel flexible, i.e. fossil gas, biogas, biomethane and hydrogen can be used as fuel [44]. For biomass-fuelled CHP systems, there are many energy conversion technologies. While a primary conversion technology is used to obtain hot water, steam, gaseous or liquid products from biomass, a secondary conversion technology is needed to transform these products into heat and electricity. An overview of major energy conversion technologies of biomass-fuelled CHP systems is provided in [12]. The main focus of this project is on CHP units based on biomass gasification. This CHP type can potentially have higher electrical efficiency than combustion-based CHP, which is the most widespread cogeneration system.
For gasification-based CHP there exist five types of gasifiers: updraft, downdraft, fluid bed, circulating fluid and entrained flow. The schematics of these gasifiers are provided in [12]. The resulting gaseous fuel can be used by boilers, internal combustion engines and gas turbines for heat and electricity production in CHP units after proper cleaning and conditioning.
The current market share of small scale CHP plants[11] based on biomass gasification is not large, mainly due to the following reasons identified in [12] for CHP units fuelled by biomass gasification products:

- The fluctuations in the gas quality can cause extreme engine wear due to contamination and unstable operational process.
- To minimize the system cost, control measurements are rarely performed. Typically this results in variable system performance.

4 Simulation of gas networks

Simulation is required for accurate development, and economically rational and sustainable exploitation of gas networks. The use of physical models of gas flow in pipes allows the prediction of systems behaviour under different conditions. At the stage of designing a network, simulation provides an accurate guide to the selection of the network structure, geometric properties of the construction and location of non-pipe elements, such as compressors and valves. Moreover, network simulation is necessary for monitoring and control of a gas system. For example, it determines the information about the flow rates within a network.

In fluid dynamics the distinction is made between steady (time independent) and unsteady (time dependent) states of flow. For a gas network, time independent simulation can be

[11]Small scale CHP plants produce less than 100 kW electrical power. If the electric capacity is smaller than 15 kWe, the system is called micro-CHP unit. In contrast to other CHP installations, which focus on heat production and consider electricity as a useful by-product, for micro-CHP units electricity is the primary product [44]. However, electricity generation is only possible if there is heat demand.

used to estimate the values of pressures at the nodes and flow rates in the pipes. Steady-state simulation is relatively straightforward, but unsuitable for the description of the dynamic nature of systems. A gas system becomes dynamic when, the construction and the amount of gas in the network allow for varying flow rates arising from the dependence of the parameters characterizing gas supply to the system or the load on time. We provide a brief description of time independent gas flow and refer to [34] for the analysis of unsteady state.

4.1 Steady-state flow

4.1.1 Formulation

The equations used in the gas industry to describe steady state gas flow are based on the general flow equation. The general flow equation in a pipe is derived in [34]. It can be expressed as follows:

$$Q_n = \sqrt{\frac{\pi^2 R_{air}}{64}} \frac{T_n}{p_n} \sqrt{\frac{\left((p_1^2 - p_2^2) - \frac{2p_{av}^2 Sgh}{ZR_{air}T}\right) D^5}{fSLTZ}}, \tag{2}$$

where:
D is the internal diameter of the pipe,
f is the friction factor,
g is the gravitational acceleration,
h is the height difference between the pipe entrance and pipe exit,
L is the length of the pipe,
p_1 is the absolute pressure at pipe entrance,
p_2 is the absolute pressure at pipe exit,
p_{av} is the flow average pressure,
p_n is the standard pressure, approximately 0.1 MPA,
Q_n is the volume flow rate at standard conditions,
R_{air} is the gas constant for air,
S is the specific gravity of the gas,
T is the absolute temperature,
T_n is the standard temperature, 288 K,
Z is the compressibility factor.

Remark
Equation (2) and equations derived from it are provided in the English system of units.

The common flow equations for a horizontal pipe are described in Appendix B. From these equations follows that for low pressure networks the flow in pipe k can be defined as

$$(Q_n)_k = S_{ij} \left(\frac{S_{ij}(p_i - p_j)}{K_k} \right)^{1/2}, \tag{3}$$

where
K_k is the pipe constant for pipe k,
p_i is the absolute pressure at node i,
$S_{ij} = \begin{cases} 1 & \text{if } p_i > p_j, \\ -1 & \text{if } p_i < p_j. \end{cases}$
For medium and high pressure networks the flow equation in pipe k is given by

$$(Q_n)_k = S_{ij} \left(\frac{S_{ij}(P_i - P_j)}{K_k} \right)^{1/m_1}, \tag{4}$$

where
$P_i = p_i^2, P_j = p_j^2$,
$m_1 = \begin{cases} 1.848 & \text{for medium pressure networks,} \\ 1.854 & \text{for high pressure networks.} \end{cases}$
The derivation of Equations (3) and (4) is provided in [34].

Remark
For simplicity, we will use Q instead of Q_n in the remainder of the chapter.

4.1.2 Kirchhoff's laws

In this section we consider the gas network illustrated in Figure 3. The network consists of four nodes and five branches. The nodes and branches are numbered[12]. Source node 1 is used as the reference node[13]. The load at this node, L_1, is the inflow in the network. Node 2, 3 and 4 are load nodes with loads equal to L_2, L_3 and L_4. The sum of L_2, L_3 and L_4 is equal to L_1. In addition, the network contains two loops, loop A and B[14]. Loop A consists of branches 1, 2 and 4, while loop B is comprised of branches 2, 5 and 3. The direction of each loop is chosen randomly.

Kirchhoff's first law
Kirchhoff's first law states that for every node the sum of the flows is equal to zero. This implies that at any node the sum of the branch flows into and out of the node is equal to the load.

[12] The branch indexes are not directly provided, but can be obtained from the indexes of branch flows. For example, Q_1 is the flow in branch 1.

[13] The reference node is considered to be independent. In general, the source node is used as the reference node, because it has a known value of pressure. However, any other node for which the value of pressure is provided can be chosen to be the reference node.

[14] A third loop consisting of branches 1, 4, 5 and 3 is not specified, because it is redundant if loop A and B are defined.

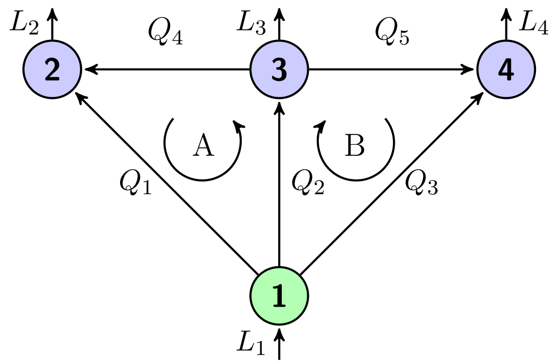

Figure 3: Gas network consisting of 4 nodes.

Applying Kirchhoff's first law to the network of Figure 3, we obtain a set of nodal equations:

$$\begin{aligned} -Q_1 - Q_2 - Q_3 \qquad\qquad &= -L_1, \\ Q_1 \qquad\qquad + Q_4 \qquad &= L_2, \\ Q_2 \qquad - Q_4 - Q_5 &= L_3, \\ Q_3 \qquad + Q_5 &= L_4. \end{aligned}$$

These equations are not linearly independent. Therefore, we assume that the equation for the reference node is redundant. The remaining equations can be written as

$$L_i = \sum_{j=1}^{m} a_{ij} Q_j, \quad i = 1, ..., n_1, . \tag{5}$$

where
m is the number of branches,
n_1 is the number of load nodes, which is equal to the total number of nodes excluding the reference node,

$$a_{ij} = \begin{cases} 1 & \text{if branch } j \text{ enters node } i, \\ -1 & \text{if branch } j \text{ leaves node } i, \\ 0 & \text{if branch } j \text{ is not connected to node } i. \end{cases}$$

Equation (5) can be expressed in matrix form:

$$\mathbf{L} = \mathbf{A}_1 \mathbf{Q}, \tag{6}$$

where
$\mathbf{L}$ is the n_1-dimensional vector of loads at the load nodes,
$\mathbf{A}_1 = [a_{ij}]_{m \times n_1}$ is the reduced branch-nodal incidence matrix,
$\mathbf{Q}$ is the m-dimensional vector of flows in branches.

Assuming that Figure 3 represents a high-pressure network, the pressure drops in the branches are related to the nodal pressures by the following system of equations:

$$\mathbf{\Delta P} = -\mathbf{A}^T\mathbf{P}, \tag{7}$$

where
$\mathbf{\Delta P}$ is the m-dimensional vector of pressure drops in branches,
$\mathbf{A}$ is the branch-nodal incidence matrix[15],
$\mathbf{P}$ is the n-dimensional vector of squared nodal pressures.

From Equation (4) follows that flows in branches depend on pressure drops:

$$\mathbf{Q} = \boldsymbol{\phi}(\mathbf{\Delta P}), \tag{8}$$

where
$\boldsymbol{\phi}(\mathbf{\Delta P})$ is the m-dimensional vector of pressure drop functions.
Combining Equation (6), (7) and (8) we obtain

$$\mathbf{L} = \mathbf{A}_1\boldsymbol{\phi}(-\mathbf{A}^T\mathbf{P}). \tag{9}$$

This equation should be solved in order to obtain the nodal pressures.

Kirchhoff's second law
Kirchhoff's second law states that the pressure drop across branches in a closed loop[16] is equal to zero.
For the network from Figure 3 the loop equations are

$$\begin{aligned} &\text{Loop A:} \; -\Delta P_1 + \Delta P_2 \qquad\quad + \Delta P_4 \qquad\quad = 0 \\ &\text{Loop B:} \qquad\qquad + \Delta P_2 - \Delta P_3 \qquad\quad + \Delta P_5 = 0 \end{aligned}$$

The pressure drop, ΔP, is positive if the direction of the branch flow coincides with the direction of the loop flow. ΔP is negative if the directions are opposite. The loop equations can be rewritten as

$$\sum_{j=1}^{m} b_{ij}\Delta P_j = 0, \quad i = 1, ..., k,$$

where
k is the number of independent loops,

$$b_{ij} = \begin{cases} 1 & \text{if branch } j \text{ has the same direction as loop } i, \\ -1 & \text{if branch } j \text{ has the opposite direction as loop } i, \\ 0 & \text{if branch } j \text{ is not in loop } i. \end{cases}$$

[15] Branch-nodal incidence matrix consists of the reduced branch-nodal matrix, $\mathbf{A}_1$, and coefficients a_{ij} for the reference nodes

[16] A loop is called closed if it starts and finishes at the same node.

In matrix form the loop equations are expressed as follows:

$$\mathbf{B}\boldsymbol{\Delta}\mathbf{P} = \mathbf{0}, \tag{10}$$

where
$\mathbf{B} = [b_{ij}]_{k\times m}$ is the branch-loop incidence matrix.

Observing that $\boldsymbol{\Delta}\mathbf{P} = \boldsymbol{\phi}^{-1}(\mathbf{Q})$, where $\boldsymbol{\phi}^{-1}(\mathbf{Q})$ is the m-dimensional vector of flow functions, Equation (10) can be written as follows:

$$\mathbf{B}\boldsymbol{\phi}^{-1}(\mathbf{Q}) = \mathbf{0}. \tag{11}$$

To obtain loop flows from this equation or nodal pressures from Equation (9), we need to solve a system of non-linear algebraic equations. Techniques based on the Newton method are generally used for this purpose. In each iteration, these methods linearize the system and apply direct or iterative solvers to the resulting linear system, which has a sparse coefficient matrix. We refer to [40] for the introduction to direct and iterative methods and focus on the Newton based techniques in the remaining part of this section.

4.1.3 Newton-nodal method

Equation (9) can be rewritten as

$$\mathbf{F}(\mathbf{P_1}) = \mathbf{A}_1\boldsymbol{\phi}(-\mathbf{A}^T\mathbf{P_1}) - \mathbf{L}, \tag{12}$$

where $\mathbf{F}(\mathbf{P_1}) \to \mathbf{0}$ if nodal pressure approximation $\mathbf{P}_1$ approaches the exact solution. Defining $f_i(\mathbf{P_1})$ as the error at node i, $\mathbf{F}(\mathbf{P_1})$ can be written as

$$\mathbf{F}(\mathbf{P_1}) = \begin{pmatrix} f_1(P_1, P_2, \ldots, P_{n_1}) \\ f_2(P_1, P_2, \ldots, P_{n_1}) \\ \vdots \\ f_{n_1}(P_1, P_2, \ldots, P_{n_1}) \end{pmatrix}.$$

The Newton-nodal method solves Equation (12) iteratively by correcting the approximations to the nodal pressures:

$$\mathbf{P}_1^{l+1} = \mathbf{P}_1^l + (\boldsymbol{\delta}\mathbf{P_1})^l\,,$$

where l is the iteration number.
The correction term $\boldsymbol{\delta}\mathbf{P_1}$ is computed using the nodal Jacobi matrix:

$$\mathbf{J}^l(\boldsymbol{\delta}\mathbf{P_1})^l = -[\mathbf{F}(\mathbf{P_1})]^l$$

with

$$\mathbf{J}^l = \begin{pmatrix} \frac{\partial f_1^l}{\partial P_1^l} & \frac{\partial f_1^l}{\partial P_2^l} & \cdots & \frac{\partial f_1^l}{\partial P_{n_1}^l} \\ \frac{\partial f_2^l}{\partial P_1^l} & \frac{\partial f_2^l}{\partial P_2^l} & \cdots & \frac{\partial f_2^l}{\partial P_{n_1}^l} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_{n_1}^l}{\partial P_1^l} & \frac{\partial f_{n_1}^l}{\partial P_2^l} & \cdots & \frac{\partial f_{n_1}^l}{\partial P_{n_1}^l} \end{pmatrix},$$

where f_i^l denotes $f_i(\mathbf{P}_1^l)$.

For Figure 3 the nodal equations are given by

$$\begin{aligned}
f_2 &= S_{12}\left(\frac{S_{12}(P_1-P_2)}{K_1}\right)^{1/m_1} + S_{32}\left(\frac{S_{32}(P_3-P_2)}{K_4}\right)^{1/m_1} - L_2,\\
f_3 &= S_{13}\left(\frac{S_{13}(P_1-P_3)}{K_2}\right)^{1/m_1} + S_{32}\left(\frac{S_{32}(P_3-P_2)}{K_4}\right)^{1/m_1} -\\
&\quad - S_{34}\left(\frac{S_{34}(P_3-P_4)}{K_5}\right)^{1/m_1} - L_3,\\
f_4 &= S_{14}\left(\frac{S_{14}(P_1-P_4)}{K_3}\right)^{1/m_1} + S_{34}\left(\frac{S_{34}(P_3-P_4)}{K_5}\right)^{1/m_1} - L_4.
\end{aligned}$$

The nodal Jacobi matrix in this case is equal to

$$\mathbf{J} = -\frac{1}{m_1}\begin{pmatrix} \left(\frac{Q_1}{\Delta P_1}+\frac{Q_4}{\Delta P_4}\right) & -\frac{Q_4}{\Delta P_4} & 0 \\ -\frac{Q_4}{\Delta P_4} & \left(\frac{Q_2}{\Delta P_2}+\frac{Q_4}{\Delta P_4}+\frac{Q_5}{\Delta P_5}\right) & -\frac{Q_5}{\Delta P_5} \\ 0 & -\frac{Q_5}{\Delta P_5} & \left(\frac{Q_3}{\Delta P_3}+\frac{Q_5}{\Delta P_5}\right) \end{pmatrix}. \tag{13}$$

In general, the nodal Jacobi matrix can be expressed as $-\mathbf{A}_1\mathbf{D}\mathbf{A}_1^T$, where $\mathbf{D}$ is a diagonal matrix with entry $\frac{1}{m_1}\frac{Q_i}{\Delta P_i}$ in row i with $i = 1, \ldots, m$. The matrix is square and symmetrical. Each diagonal entry of $\mathbf{J}$ is associated with a particular load node and is equal to the sum of expression $\frac{Q}{\Delta P}$ for all the branches connected to that node. This sum is always positive, because Q is positive if ΔP is positive and vice versa.
Each off-diagonal entry corresponds with the connection between two load nodes and consists of the expression $-\frac{Q}{\Delta P}$ for the branch that connects the two nodes.
Furthermore, in a gas network a node is directly connected to at most 5 other nodes. Therefore, $\mathbf{J}$ becomes sparser as the number of nodes in the network increases.

High degree of sparsity and simplicity are the main advantages of the Newton nodal method. The considerable disadvantage is its poor convergence, caused by the exponential $\frac{1}{2}$ or $\frac{1}{m_1}$ in the nodal equations. These terms are computationally inefficient and make the method sensitive to starting values.

4.1.4 Newton-loop method

The Newton-loop method is based on the branch flow within the loops in the network. It is used to solve a set of loop equations, provided in Equation (11). In order to provide the description of the Newton-loop method, we introduce the so-called loop flow.

Definition 3 *The loop flow is the flow correction which is added to the branch flow in order to obtain the exact solution.*

Denoting the vector of loop flows by $\mathbf{q}$, the branch flow can be expressed as follows:

$$\mathbf{Q} = \mathbf{Q}^0 + \mathbf{B}^T\mathbf{q},$$

where $\mathbf{Q}^0$ is the initial approximation of the branch flows.
Thus, Equation (11) can be rewritten as

$$\mathbf{B}\boldsymbol{\phi}^{-1}(\mathbf{Q}^0 + \mathbf{B}^T\mathbf{q}) = \mathbf{0}.$$

Equivalently, Kirchhoff's second law may be given by

$$\mathbf{F}(\mathbf{q}) = \mathbf{B}\boldsymbol{\phi}^{-1}(\mathbf{Q}^0 + \mathbf{B}^T\mathbf{q}), \tag{14}$$

where $\mathbf{F}(\mathbf{q}) \to \mathbf{0}$ as $\mathbf{q}$ approaches the exact values of the loop flows.
Under the assumption that $f_i(\mathbf{q})$ is the error in loop i, the left-hand side of Equation (14) equals

$$\mathbf{F}(\mathbf{q}) = \begin{pmatrix} f_1(q_1, q_2, \ldots q_\kappa) \\ f_2(q_1, q_2, \ldots q_\kappa) \\ \vdots \\ f_\kappa(q_1, q_2, \ldots q_\kappa) \end{pmatrix},$$

where κ is the number of independent loops in the network.
The branch flow approximation is corrected in every iteration:

$$\mathbf{q}^{l+1} = \mathbf{q}^l + \boldsymbol{\delta}\mathbf{q}^l,$$

where the iteration term is obtained from the equation

$$\mathbf{J}^l\boldsymbol{\delta}\mathbf{q}^l = -[\mathbf{F}(\mathbf{q})]^l.$$

The loop Jacobi matrix $\mathbf{J}^l$ has the following structure:

$$\mathbf{J}^l = \begin{pmatrix} \frac{\partial f_1^l}{\partial q_1^l} & \frac{\partial f_1^l}{\partial q_2^l} & \cdots & \frac{\partial f_1^l}{\partial q_\kappa^l} \\ \frac{\partial f_2^l}{\partial q_1^l} & \frac{\partial f_2^l}{\partial q_2^l} & \cdots & \frac{\partial f_2^l}{\partial q_\kappa^l} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_{n_1}^l}{\partial q_1^l} & \frac{\partial f_{n_1}^l}{\partial q_2^l} & \cdots & \frac{\partial f_\kappa^l}{\partial q_\kappa^l} \end{pmatrix}.$$

For illustrative purposes, we apply the Newton-loop method to the network illustrated in Figure 3. We identify two loop flops, q_A and q_B. The composition and direction of q_A and q_B coincide with those of loop A and B, respectively.

From Equation (4) follows that

$$\Delta P_k = S_k K_k (S_k Q_k)^{m_1}$$

with $S_k = \begin{cases} 1 & \text{if } Q_k \text{ is positive,} \\ -1 & \text{if } Q_k \text{ is negative.} \end{cases}$

Thus,

$$\begin{aligned} f_A &= -S_1 K_1 \left(S_1(Q_1^0 - q_A)\right)^{m_1} + S_2 K_2 \left(S_2(Q_2^0 + q_A + q_B)\right)^{m_1} \\ &\quad + S_4 K_4 \left(S_4(Q_4^0 + q_A)\right)^{m_1}, \\ f_B &= S_2 K_2 \left(S_2(Q_2^0 + q_A + q_B)\right)^{m_1} - S_3 K_3 \left(S_3(Q_3^0 - q_B)\right)^{m_1} \\ &\quad + S_5 K_5 \left(S_5(Q_5^0 + q_B)\right)^{m_1}. \end{aligned}$$

The loop Jacobi matrix in this case is equal to

$$J = \begin{pmatrix} K_1|Q_1|^{m_1-1} + K_2|Q_2|^{m_1-1} + K_4|Q_4|^{m_1-1} & K_2|Q_2|^{m_1-1} \\ K_2|Q_2|^{m_1-1} & K_2|Q_2|^{m_1-1} + K_3|Q_3|^{m_1-1} + K_5|Q_5|^{m_1-1} \end{pmatrix}.$$

Generally, the loop Jacobi matrix can be written as $\mathbf{BMB}^T$ with $\mathbf{M} = \text{diag}(m_1 K_i |Q_i|^{m_1-1})$, $i = 1, 2, \ldots, m$. The loop Jacobi matrix has the following properties:

- It is square and symmetrical.
- Each diagonal entry corresponds with a particular loop and consists of the sum of the expressions $K|Q|^{m_1-1}$ for the branches comprising that loop.
- Diagonal entries are positive.
- Each off-diagonal entry corresponds with a connection between two loops and consists of expression $\pm K|Q|^{m_1-1}$ for the mutual branches.
- If the flow in the mutual branches has the same direction in both loops, the off-diagonal entry is positive. Otherwise, it is negative.

The main drawback of the Newton-loop method is that a network has to be split in loops. Moreover, it is desirable that the loops have a low number of interconnections, so the degree of sparsity of the Jacobi matrix would be relatively high.
On the other hand, the method has good convergence characteristics [34].

4.1.5 Newton loop-node method

The Newton loop-node method combines the Newton-nodal and Newton-loop method to obtain good convergence characteristics and a low degree of sparsity of the Jacobi matrix. To describe the method, we introduce a number of definitions from graph theory.

Definition 4 *A connected graph without loops is called a tree.*

Definition 5 *If a tree T is a subgraph of a connected graph G and includes all its nodes, then T is called a dendrite (spanning-tree) of G.*

Definition 6 *Tree branches are the branches that belong to a dendrite T, cords are all other branches of G.*

Definition 7 *A subgraph of G formed by the collection of cords is called cotree of T.*

Analogously to the Newton-loop method, the Newton loop-node method solves the set of loop equations:

$$\mathbf{B}\boldsymbol{\phi}^{-1}(\mathbf{Q}) = \mathbf{0}.$$

Using Taylor approximation for $\boldsymbol{\phi}^{-1}(\mathbf{Q})$, i.e.

$$\boldsymbol{\phi}^{-1}(\mathbf{Q})^{l+1} = \boldsymbol{\phi}^{-1}(\mathbf{Q} + \boldsymbol{\Delta}\mathbf{Q})^{l} = \boldsymbol{\phi}^{-1}(\mathbf{Q})^{l} + \mathbf{R}^{l}\boldsymbol{\Delta}\mathbf{Q}^{l} \tag{15}$$

with $\mathbf{R} = \frac{\partial\boldsymbol{\phi}^{-1}(\mathbf{Q})}{\partial\mathbf{Q}}$, loop flow equations are transfered into a set of node flow equations (see [34]):

$$\mathbf{J}^{l}\mathbf{P}_{1}^{l+1} = \mathbf{A}_{1}\left(\mathbf{R}^{l}\right)^{-1}\left(\boldsymbol{\Delta}\mathbf{P}^{l} + \mathbf{A}_{2}^{T}\mathbf{P}_{2}\right), \tag{16}$$

where
$\mathbf{J}$ is the nodal Jacobi matrix,
$\mathbf{P}_1$ is a vector of unknown nodal pressures,
$\mathbf{P}_2$ is a vector of known nodal pressures,
$\mathbf{A}_1$ is the branch-nodal incidence matrix corresponding with unknown pressures,
$\mathbf{A}_2$ is the branch-nodal incidence matrix corresponding with known pressures.

Equation (16) is solved to obtain nodal pressures $\mathbf{P}_1$.
Furthermore, it should be noted that Equation (15) can be rewritten as

$$\boldsymbol{\Delta}\mathbf{P}^{l+1} = \boldsymbol{\Delta}(\mathbf{P})^{l} + \mathbf{R}^{l}\boldsymbol{\Delta}\mathbf{Q}^{l},$$

because $\boldsymbol{\Delta}\mathbf{P} = \boldsymbol{\phi}^{-1}(\mathbf{Q})$. Equivalently,

$$\boldsymbol{\Delta}\mathbf{Q}^{l} = \left(\mathbf{R}^{l}\right)^{-1}\left(\boldsymbol{\Delta}\mathbf{P}^{l+1} - \boldsymbol{\Delta}\mathbf{P}^{l}\right).$$

From $\boldsymbol{\Delta}\mathbf{P} = -\mathbf{A}^{T}\mathbf{P}$ follows that

$$\boldsymbol{\Delta}\mathbf{Q}^{l} = \left(\mathbf{R}^{l}\right)^{-1}\left(-\mathbf{A}^{T}\mathbf{P}^{l+1} - \boldsymbol{\Delta}\mathbf{P}^{l}\right).$$

For the cotree part of the network we obtain

$$\boldsymbol{\Delta}\mathbf{Q}_{c}^{l} = \left(\mathbf{R}_{c}^{l}\right)^{-1}\left(-\mathbf{A}_{c}^{T}\mathbf{P}^{l+1} - \boldsymbol{\Delta}\mathbf{P}_{c}^{l}\right). \tag{17}$$

From Equation (17) the corrections to the chord flow are computed and hence the new values for the chord flow can be obtained:

$$\mathbf{Q}_{c}^{l+1} = \mathbf{Q}_{c}^{l} + \boldsymbol{\Delta}\mathbf{Q}_{c}^{l}. \tag{18}$$

To obtain the new tree branch flows $\mathbf{Q}_t^{l+1}$, $\mathbf{L} = \mathbf{A}_1\mathbf{Q}$ should be partitioned into dendrite and cotree elements, i.e.

$$\mathbf{L} = \mathbf{A}_{1t}\mathbf{Q}_t + \mathbf{A}_{1c}\mathbf{Q}_c. \tag{19}$$

Rearranging Equation (19), we obtain:

$$\mathbf{Q}_t = \mathbf{A}_{1t}^{-1}\left(\mathbf{L} - \mathbf{A}_{1c}\mathbf{Q}_c\right).$$

Thus, according to the above equation the new tree branch flows can be computed from the chord flows. Subsequently, the branch flows are used to provide the set of nodal equations for the next iteration.

For Figure 3 the nodal Jacobi matrix is provided in Equation (13).
$\left(\mathbf{\Delta P}^l + \mathbf{A}_2^T\mathbf{P}_2\right)$ from Equation (16) is equal to:

$$\left(\mathbf{\Delta P}^l + \mathbf{A}_2^T\mathbf{P}_2\right) = \begin{pmatrix} \Delta P_1 - P_1 \\ \Delta P_2 - P_1 \\ \Delta P_3 - P_1 \\ \Delta P_4 \\ \Delta P_5 \end{pmatrix}.$$

After $\mathbf{P}_1^{l+1}$ is computed from Equation (16), the corrections to the chord flows are obtained from the nodal pressures:

$$\Delta Q_4 = R_{44}^{-1}\left((P_3 - P_2) - \Delta P_4\right),$$
$$\Delta Q_5 = R_{55}^{-1}\left((P_3 - P_4) - \Delta P_5\right).$$

Subsequently, the new values of the chord flow are computed according to Equation (18). The tree branch flows are calculated from the chord flows by tracing the tree back to the reference node:

$$Q_1 = L_2 - Q_4,$$
$$Q_2 = L_3 + Q_4 + Q_5,$$
$$Q_3 = L_4 - Q_5.$$

5 Collaboration between TPM and Numerical Analysis group

There is a number of research questions concerning smart gas grids for which the collaboration between the scientific groups at the TPM faculty and Numerical Analysis group of the EEMCS faculty can provide unique and valuable insight. For such problems the solution approach consists of three complementary parts:

- topological structure,

- institutional design,
- physical simulation.

The investigation of topological structure is performed by Energy and Industry section of the TPM faculty. The system topology depends on economic and technical parameters, such as robustness and construction costs. Generally, the topology is constructed by solving an optimization problem using standard methods from graph theory or Agent Based Modeling. The topological structure is typically required for planning and routing networked infrastructure, such as power and gas grid.

The simulation of physical processes within a network is carried out by the Numerical Analysis group of the EEMCS faculty. It implies formulation and numerical treatment of a mathematical model describing some given physical process. The mathematical problem is a simplified image of the process based on the mathematical relations between quantities. Its numerical treatment includes the discretization, choice or construction of an appropriate numerical method and its implementation. The treatment of time independent gas networks is briefly described in Chapter 4.

The research concerning institutional design is performed by Economics of Technology and Innovation section of the TPM faculty. The analysis of institutional design is required to make the solution of a given problem more applicable to real-life situations. In addition, it can be used to decrease the number of feasible options for topological structure.

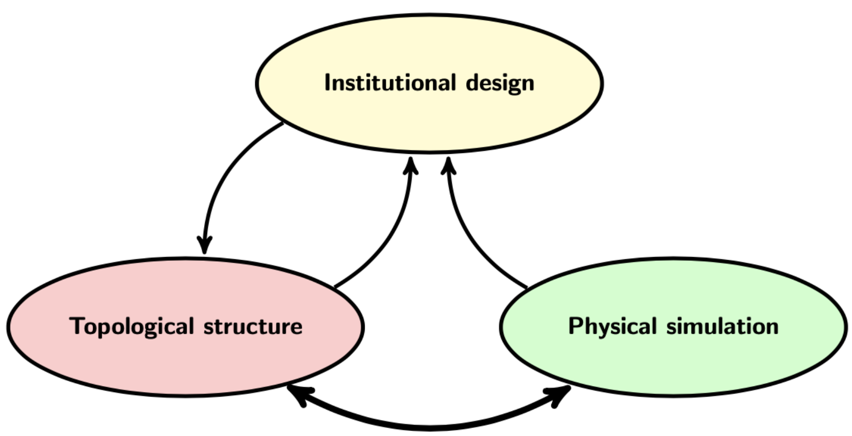

Figure 4: The collaboration between scientific groups.

As shown in Figure 4, these research areas are directly or indirectly interconnected with each other. The interplay between these research on topological structure and physical simulation can be seen as an iterative procedure required for the optimization of technical

aspects of the problem.
Institutional design adds a socio-economic dimension to the solution and can be used for reflecting on topological design.

Moreover, the scheme for collaborating, demonstrated in Figure 4, is supposed to be realized during the project on system integration. This project is developed to investigate the possibilities for the design of autonomous local energy supply systems in the Netherlands. As has been mentioned in Chapter 2, there is a tendency among local Dutch communities to make the transition towards more sustainable and decentralized energy system. Therefore, the primary purpose of the system integration project is to create tools for designing and determining the structure and size of autonomous energy regions. Although no in-depth scientific analysis has yet been performed on this subject, some relevant previous work can be found in [3, 5, 10, 22, 23, 32, 35].

6 Defining research questions

6.1 Natural gas network

6.1.1 Further introduction of H-gas within Dutch gas network

What is the most economical manner to transform the Dutch gas supply system?
Obviously, further introduction of H-gas requires a closer interplay of the H-gas HTL grid with the remaining part of the transmission network and distribution network. This implies that different parts of the network will be interconnected and many network components will have to be adapted.

What safety regulations are required for the transition to H-gas?
New safety regulations for the gas supply system (pipelines, supply stations, etc.) should be outlined.

Is it possible to develop an affordable and accurate system for monitoring and control of the quality, pressure and flow of gas in the Dutch gas supply network?
In [27] smart gas grids are defined as active gas networks with interactive functionalities to integrate multiple energy sources and services, and empower consumers to use and generate energy more efficiently. According to [43], monitoring and control system forms a basis of such networks. These systems are based on, for instance, the information from the end-user.

Is it possible to combine the transition to H-gas with further integration of non-conventional gases such as biomethane and hydrogen?
From the financial point of view, it can be more attractive to adapt the Dutch gas supply network simultaneously to H-gas and non-conventional gases. The European Union encourages the use of renewable energy sources, including many non-conventional gases.

Relevant previous work

- The research presented in [20].
- Discussion regarding harmonization on the European level in [24, 28].
- Recomendation of Marcogaz regarding non-conventional gases, [26].

Alternatively, the following questions concerning the natural gas network can be investigated:

- security of the Dutch natural gas supply,
- integration with electricity network.

6.2 Biogas and biomass gasification

When does the use of biomass for gasification or biogas production lead to environmental and financial benefit?
Although biomass is a renewable energy source and the burning of biogas releases the same amount of carbon dioxide previously captured within the organic matter, there are several ideological barriers for its widespread use. For instance, there exists mounting concern that the biodiversity will be reduced. The displacement of native ecosystem can lead to technical issues such as the loss of crop ability to cope with blights and food shortages, if energy crops replace food crops [4].
In [30] the benefits from biogas CHP plants are considered, but the scope is limited to the hog-farming states in the USA. It is concluded that while financial benefits vary depending on the location, environmental benefits are consistently high. In fact, biogas CHP units reduce ozone precursor pollutants, which cause significant problems in the hog-farming states.

6.2.1 Construction and operation of biogas injection plants

To what extent should the process of production and injection of biogas be centralized?
Digester, purification, upgrading, mixing and, if applicable, odorization installations are required for the production of biogas and its injection into the natural gas grid. The location of these installations with respect to each other and the feed point should be optimal from the economic, environmental and technical perspective.
Furthermore, it is important to determine the optimal location of for the injection plants. According to [43], it is economically not feasible to inject biomethane into the transmission grid. Therefore, the choice should be made between high and low pressure distribution lines. It is also important to determine the exact geographical location of the feed point to limit capital and construction costs.

What is the preferable configuration of a biogas plant?
An innovative design can improve the efficiency and robustness of the biogas plants. Numerical simulation is commonly used for such purposes.

Is it possible to develop an affordable and accurate system for monitoring and control of the quality, pressure and flow of the natural gas/biomethane mixture?
Monitoring and control system should be developed to meet the gas demand and prevent safety issues. The obtained data can be used to improve the system design (e.g. the construction of mixing devices).

Is it possible to increase the flexibility of the biomethane production process in order to cope with a variable gas demand?
In rural areas the gas demand varies strongly during the year. The production process of biomethane is very inflexible [43]. Therefore, the biomethane is limited by the gas demand in the summer. This implies that the use of biogas potential is not optimal.

Relevant previous work

- The research of Weidenaar T. presented in [42, 43].
- The research of Hegeveld E. presented in [15].
- Recomendation of Marcogaz, [26].
- The research of Zachariah presented in [48].

6.2.2 Construction and operation of CHP plants fuelled by biogas or gasified biomass

Under what circumstances is the construction of a CHP plant fuelled by biomass derived gases financially profitable? What is the preferable configuration of the plant?
Due to the local nature of biomass and inflexibility of its production, biomass-fuelled CHP plants are not eminently suitable for households. However, for areas where the connection to power and heat networks is problematic, the construction of a biomass-fuelled CHP plant is a viable option. Furthermore, farmers, producing biomass, can use micro-CHP plants for their farmhouses, greenhouses and the product treatment, e.g. the conversion of liquid manure to fertilizer, cleaning and disinfection of the milking equipment [4].
On the other hand, the configuration of the CHP plant is very important. For instance, the type of the prime mover (e.g. turbine) and size can strongly influence the efficiency and life time of the unit [4, 41] and, hence, the corresponding operating costs. Utilization of computational methods may be used to provide basis for selection of optimal configuration for new and modified devices [37].

What technological and operational changes are required for the use of gasified biomass or biogas in CHP plants?

Although CHP plants are fuel flexible, the use of biogas or gasified biomass can influence their efficiency and life time [21, 4]. The main issues are related to fuel properties such as low calorific value and relatively high water content. For example, firing biogas instead of natural gas in existing CHP system based on gas turbine can cause overheating of turbine blade [21]. The introduction of technological adjustments and operational restrictions is required to prevent such side-effects. This is also important for the design of new CHP plants, because the composition of biomass derived gases can vary depending on the biomass source.

Is it possible to develop a sophisticated tool for for troubleshooting?
In case of the failure of one or several components comprising a CHP plant, a systematic approach is required in order to make the process operational again. In [37] it is suggested that computational methods such as CFD can be used to develop sophisticated troubleshooting technology that provides insight in the situation and evaluates remedying measures.

Is it possible to construct an affordable CHP network (partially) fuelled by biomass derived gases?
CHP network consists of a number of CHP installations used to satisfy total thermal demand of a large site or a collection of appliances [4]. The design of a CHP network should be optimized in order to make its construction and operation financially beneficial.

What is the optimal manner to integrate CHP plants fuelled by biomass derived gases with other renewable energy technologies?
A considerable disadvantage of wind and solar energy is the variability of their production. The integration of these renewable energy sources with CHP plants fuelled by biomass derived gases can create favourable conditions for dealing with the fluctuations in energy production.

Relevant previous work

- The overview of Thilak Raj N. et al. provided in [38].
- The research of Walla C. and Schneeberger W. presented in [41].
- The research of Papadopoulos D. and Katsigiannis P. presented in [36].
- The research of Kang D. et al. presented in [21].
- The research of Lund H. and Münster E. from [25].

A Use of biogas

In this section, we discuss a number of applications of biogas that may be relevant for the smart gas grids, but are not included in Section 3.

A.1 Supply of current to electricity network

The operation mode of a gas engine within a public electricity network depends on whether it

- covers peak load,
- covers basic load
- supplies its own energy requirements and feeds the surplus into the network [9].

Complex gasholders and large power stations are needed for peak load covering, hence plant design in that case is different from that for basic load covering.

Biogas plants are usually used to cover the basic load, because its production is very inflexible. Normally, they are constructed at regions, where the power network is not available and the connection of combined heat and power generation plant (CHP) to the public power network is problematic [9].

A.2 Heat production

Biogas has a calorific value of 21-23 MJ/m^3 [2]. Therefore, the combustion of biogas in a boiler is suitable for the generation of hot water and steam. Since heat production from biogas remains reasonably constant over the whole year, it is not suitable for households, but can be used for industrial plants, greenhouses, swimming pools, etc.
On the one hand, heat production from biogas has a number of disadvantages, such as

- the boilers utilizing biogas have relatively large size, i.e. the boilers are oversized compared to oil and natural gas equipment, because the quality of biogas is lower;
- the boilers are sensitive to corrosion, i.e. a harmful condensate can form in the flues if the boiler is running at temperature lower than 65°C due to the corrosive nature of biogas.

On the other hand, capital and operating costs are sufficiently low, because almost no treatment is required prior to the combustion of biogas [2]. The construction of steam boilers is slightly more complex, because they have to be supplied with softened potable water. This water is pretreated to dissolve oxygen and typically contains chemical additions to prevent foaming and corrosion.

A.3 Combined heat, power and cooling generation

It is possible to use excess heat from the gas engine to provide not only heat, but also cooling. In this case the process is called trigeneration, or combined heat, power and cooling (CHPC). The cooling cycle consists of four fundamental stages: compression, condensation, expansion and evaporation [2].
At the first stage, electricity is used to compress the refrigerant, a gas that carries the energy. This is done by increasing the temperature of the refrigerant to above ambient temperature.
During the condensation stage, the refrigerant is cooled in the condenser which acts as a radiator to enable the heat transfer from the refrigerant to the atmosphere.
After that, the liquid refrigerant passes through the expansion valve in order to reduce the pressure created by the compressor.
The evaporation process is required to complete the cycle. During this process, the refrigerant passes through the evaporator which allows heat transfer from the outside air to the refrigerant.

B Common flow equations

In this section, we present several common flow equations for a horizontal pipe. The main differences between these equations arise from the definition of the friction factor f.

Lacey's equation
Lacey's equation, which is used for low pressure networks operating between 0-75 mbar gauge, has the following form:

$$Q_n = 5.72 \times 10^{-4} \sqrt{\frac{(p_1 - p_2)D^5}{fSL}},$$

where the unit for p, D and L is mbar, mm and m, respectively.
The value of the friction factor is obtained from Unwin's formula:

$$f = 0.0044 \left(1 + \frac{12}{0.276D}\right).$$

Alternatively, the friction factor can be assumed equal to 0.0065 for all pipes providing us with Pole's equation:

$$Q_n = 7.1 \times 10^{-3} \sqrt{\frac{(p_1 - p_2)D^5}{SL}}.$$

The Polyflo equation
For medium pressure networks operating between 0.75-7.0 bar gauge the Polyflo equation is used:

$$Q_n = 7.57 \times 10^{-4} \frac{T_n}{p_n} \sqrt{\frac{(p_1^2 - p_2^2) D^5}{f S L T}}$$

with bar as unit for pressure.

To define the friction factor, we need to introduce the Reynolds number. The Reynolds number is a dimensionless number characterizing the gas flow conditions. It can be calculated as follows:

$$Re = \frac{D w \rho}{\mu},$$

where
w is the velocity of gas,
ρ is the density of gas,
μ is the coefficient of the dynamic viscosity (i.e. the gas resistance to flow).
An alternative expression for the Reynolds number is given by

$$Re = \frac{4 Q \rho}{\mu D \pi}, \tag{20}$$

where Q is the volume flow rate.
Under the assumption that the physical properties of the gas do not change, Equation (20) can be written as

$$Re = C \frac{Q}{D} \tag{21}$$

with $C = \frac{4\rho}{\mu\pi}$.

The value of f is obtained from the transmission factor:

$$\sqrt{\frac{1}{f}} = 5.338 \, (Re)^{0.076} \, E, \tag{22}$$

where E is the efficiency factor[17].
Taking into account Equation (21) applied to natural gas, Equation (22) becomes equivalent to

$$\sqrt{\frac{1}{f}} = 11.98 \times E \left(\frac{S Q_n}{D} \right).$$

[17]In general, E varies between 0.8 and 1. The value of 1, for instance, corresponds with a 100% efficiency of a perfectly smooth and clean pipe.

The Panhandle 'A' equation
The Panhandle 'A' equation is generally applied to high-pressure networks operating above 7.0 bar gauge:

$$Q_n = 7.57 \times 10^{-4} \frac{T_n}{p_n} \sqrt{\frac{(p_1^2 - p_2^2) D^5}{f S L T Z}},$$

where the unit for p is bar.
The friction factor is obtained from

$$\sqrt{\frac{1}{f}} = 14.94 \times E \left(\frac{S Q_n}{D} \right)^{0.73}.$$

The Weymouth equation
An alternative equation for high-pressure systems is Weymouth equation applicable in the fully-turbulent flow region. It uses general flow equation with the friction factor equal to

$$\sqrt{\frac{1}{f}} = 20.64 D^{\frac{1}{6}} E.$$

A number of frequently used flow equations not presented in this report can be found in [7].

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