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Modelling and Simulation of the German Gas Transmission Network with Hydrogen Blending

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Summary

This study investigates the behaviour of the German transmission gas network infrastructure with and without green hydrogen injection. Based on the simulation results of different scenarios, the challenges and criticality that arise with hydrogen blending are evaluated and analysed in detail.

One of the main aims of this study is to simulate and evaluate the gas network steady-state simulation using open-source-only datasets and tools. To achieve this, the natural gas consumption data of Germany is first studied. After comparing two different open-source datasets, the dataset `DemandRegio` is chosen, which provides hourly data for gas consumption in Germany with a NUTS-3 spatial resolution, so for each of the German districts. Then, in order to take into account the exchange of natural gas with the neighbouring countries, the import and export data are provided by the German Network Agency (German: Bundesnetzagentur) with a daily resolution. For the network topology, the `SciGRID_gas IGGIELGN` dataset is used. It contains information about the pipelines, the consumers, entry and exit points, compressors, storage, and so on. After all the data required for the simulation are analysed and processed, the simulation is performed using the open-source tool `GasNetSim`, which is a relatively newly developed tool that can perform steady-state gas network simulations. In this tool, the gas mixture compositions and properties are modelled and calculated during the simulation, therefore it can be used to study gas networks with various natural gas compositions or hydrogen injection.

The obtained results show the nodal pressure and flow rate in each pipeline of this transmission network, highlighting the pipelines with the highest flow rate and the ones with the highest pressure drop. The knowledge of these parameters is vital for a secure gas network operation.

In addition, the simulation results with hydrogen rejection offer a good basis for regulating the amount of hydrogen that can be injected into the natural gas network, so that it does not exceed the permitted limit.

It is worth mentioning that this study is limited by the lack of information on the controllable facilities, e.g. compressor stations. However, the results of this study still offer significant insights of the network operation and they also suggest

potential necessary improvements in the open-source datasets.

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Acronyms

ANN
: Artificial Neural Network

CTS
: Commerce, Trade and Services

ECM
: Error Correction Model

EU
: European Union

GA
: Genetic Algorithm

GDP
: Gross Domestic Product

LNG
: Liquefied Natural Gas

ODE
: Ordinary Differential Equation

RES
: Renewable Energy Sources

SNG
: Synthetic Natural Gas

TSO
: Transmission System Operator

BNetzA
: Bundesnetzagentur

OSM
: OpenStreetMap

PV
: Photovoltaic

P2H
: Power-to-Hydrogen

TEF
: Transmissible Energy Factor

AGEB
: AG Energiebilanzen

Chapter 1

Introduction

1.1 The role of gas grids in the energy system

Climate change is one of the most important challenges of modern days. The 2011-2020 decade was the warmest recorded, with the global average temperature reaching 1.1 °C above pre-industrial levels [1]. An increase of 2 °C compared to the temperature in pre-industrial times is linked with serious adverse effects on the environment and human health [2]. Some consequences of global warming are, in fact, frequent and intense heat waves, extreme weather, an increase in the sea level, ocean acidification, and many more. For this reason, the international community recognises the need to restrict global warming below 2 °C and pursue efforts to limit it to 1.5 °C [3].

In order to limit the temperature increase, it is vital to reduce greenhouse gas emissions. Consequently, all the EU member states have pledged to make the EU the first climate-neutral continent by 2050 [4]. To accomplish this goal, the emissions have to be reduced by no less than 55% by 2030, with respect to 1990 levels [4].

In order to decarbonise the energy sector, renewable energy sources play an important role. In 2021, renewable energy represented 21.8% of the gross final energy consumed in the EU [5] [6]. In the same year, in Germany, renewable energy sources accounted for 39.8% of the gross electricity production and wind power in particular accounted for 19.5% [7]. The main problem with renewable energy sources is their intermittency because of the uncertainties of the available energy from sunshine and wind. In particular, wind availability may not correspond to the time of day or seasonal power needs for many countries [8]. Therefore, electrical flexibility is necessary for an electricity system with high renewable energy penetration, so that the balance between power generation and demand can be maintained.

Power-to-gas is a promising technology that consists of the production of fuel, in the most simple case hydrogen, from electricity produced by renewable energy sources, as investigated in this work. So the excess power produced by RES is converted, through electrolysis, into hydrogen, which can be then injected into the natural gas grid. This sector coupling between electricity and gas also helps the operation of the power grid because unexpected power injections by wind parks create unbalances between the generated electric power and the needed power [9].

In the direction of RES penetration in the power sector, hydrogen could be the “missing link” to supply renewable energy to those sectors for which complete electrification would be difficult, like high-grade heat industrial processes, aviation or international transport, but it could also contribute to greening the existing gas grid [10].

However, the electricity sector is only a part of the broader energy sector, which includes the heating, transportation sectors, and so on. Among different energy sectors, the gas sector plays a crucial role. In 2022, the gas-fired generation represented more than 20% of global electricity generation [11], while it accounted for 23.3% on the total energy mix for the European Union in 2021 [12]. In particular, the gas pipeline network plays a significant role in transporting and distributing natural gas and it is in charge of transporting the fuel from production and extraction sites to end-users.

In Europe, one of the biggest gas markets is Germany. In fact, in the last quarter of 2022, Germany consumed the largest amount of gas among the EU countries [13] and in the future this country will continue to import natural gas. Furthermore, its massive gas network infrastructure is a closely intermeshed network with a total length of around 511,000 km [14]. With this in mind, gas grids gain importance as a means to the decarbonisation of the energy industry.

It is therefore possible to say that the gas network with hydrogen injection is a complex system that has to ensure safe and predictable operation, therefore it has to be carefully monitored and any changes to this infrastructure have to be scrupulously studied. A reliable simulation of the gas grid is then essential to ensure its safe and predictable operation. However, because of the lack of measurement and data transparency, often related to the non-disclosure of sensitive data, there exists a gap between the real network operation and research.

Hence, this work aims to develop and evaluate a steady-state German gas transmission network simulation model using only open-source datasets and tools.

1.2 Gas demand estimation

There are several ways in which it is possible to estimate the natural gas demand, some of them are described in the papers presented below.

In [15] the authors focus on demand analysis, in particular on the demand of natural gas by the residential and commercial sectors. The major themes of this paper are the formulation of a demand function for assets whose consumption is related to their stocks, and the estimation of the parameters of the demand function.

In [16] a model that describes the hypothetical natural gas demand, is presented. The model is based on the average trend of the economic development during recent decades and the result is burdened with an error resulting from the use of average data. The adjusted model expresses good compatibility with the natural gas demand for the period 1995–2000, however the authors admit that the error on the results may reach 20%.

The paper [17] uses the heating degree-day method to determine the natural gas consumption by residential heating in Turkey. In order to perform this estimation, at first only cities located nearby the existing, under construction, and planned natural gas pipelines are chosen. For these cities, degree-days, population and resident distribution records are obtained and these data are utilized to estimate the nation-wide natural gas demand.

Another approach to estimate the gas consumption is related to genetic algorithms (GA). In particular, in the paper [18] such algorithms are used for the estimation of fossil fuels demand in Turkey. In particular, GA demand estimation models are developed to estimate the future coal, oil and natural gas demand values based on population, gross national product, import and export figures. According to the authors, GA is preferable to other methods (e.g. fuzzy logic, neural networks, etc.) because it does not need many parameters for future estimations.

In [19], an adaptive network-based fuzzy inference system is used in order to estimate the natural gas demand. The input variables needed are: day of the week, demand on the same day in the previous year, demand in the day before and two days before. The authors claim that this method provides more accurate results than Artificial Neural Network (ANN) and conventional time series approach.

The paper [20] uses time series decomposition and multiple linear regression to estimate the gas consumption. In particular, to study the effects of cycling, the data were gathered from the same months of successive years.

Another interesting work is [21]. The goal of $SciGRID_gas$ is to automatically generate a gas transmission network dataset for Europe. Regarding, in particular, the CONS dataset, several different datasets and input variables, such as spatial framework, gas consumed, and number of households, are used. This gas demand was generated through an interaction of independent variable information such as Gross Domestic Product (GDP), temperature etc., in combination with heuristic models, resulting in a daily time series of gas consumption spanning the years 2010 to 2019.

The project DemandRegio [22] consists of a toolkit called “disaggregator” that aims to provide temporal and spatial disaggregation of the demands of electricity, heat and natural gas for Germany. The final consumption is broken down into the three main energy sectors: private households, commercial, trade and services (CTS) and industry.

Since the central theme of this thesis is not mainly related to gas demand estimation, open-source data about the gas consumption in Germany that are directly available are preferable.

1.3 Gas network simulation

Gas network simulation has gained importance since the 1980s and several studies about this subject have already been performed [23]. The aim of this section is to review these studies highlighting their main findings but also what can be improved by new investigations on this topic.

An early example of gas network simulation can be found in A. J. Osiadacz's work [23]. In this paper, the author provides a method for the steady-state simulation of a generic network, including as well controllable elements such as compressors, regulators and valves. To validate his method, the author provides two examples: the first one consists of a meshed network with 25 nodes, and the second is a simpler network studied with two different compression ratios at the compressors.

Another work that is worth mentioning is [24]. The authors compare finite volume method and finite difference method for the discretisation of the incompressible isothermal Euler equation, showing the advantages of the first one with respect to the latter. To simulate the system through differential algebraic equations, they propose the direction following the ordering of the edges, this allows the authors to propose an efficient preconditioner to solve the differential algebraic equations.

The focus of [25] is on the modelling of transient simulations of gas transport. Apart from pipelines, the modelling approach also includes other network elements such as valves, resistors i.e. virtual elements that resemble the existing structures that generate resistance, and compressors. In this work, the authors also present a modular gas network model as well as four benchmarks, which enable testing of extensions of this basic model as well as implementations of associated solvers.

In [26] a novel mathematical method for the simulation of a steady-state nonlinear natural gas network is developed and proposed. The proposed method is tested with two approximate models of the Irish natural gas transmission method, the results are compared and validated against the Newton-Raphson method in MATLAB and the commercial software `SAInt`.

The paper [27] presents the `morgen` (Model Order Reduction for Gas and Energy Networks) software platform. This tool enables the testing of various combinations of models, solvers, and model reduction methods for gas network simulation. The goal of `morgen` is to find the best model reduction method or best reduced order model for a network by heuristic comparison.

1.4 Hydrogen blending

The effect of hydrogen on an X80 pipeline steel is exemplified in the work undertaken by [28]. X80 pipeline steel finds frequent application in the transportation of natural gas, and this type of steel undergoes concurrent hydrogen infiltration, leading to embrittlement. The main findings of this study highlighted that the presence of hydrogen leads to a noticeable increase in the rate of fatigue crack growth, as a consequence the fatigue life of the pipeline is considerably decreased. Therefore when blending hydrogen in the network is important to consider the material's sensitivity to embrittlement.

An example of gas network simulation that includes hydrogen blending into the natural gas network can be found in the paper [29]. In this paper, a gas network modelling algorithm is proposed and its predictability is widely explored. Then, the numerical simulation of a regional-scale natural gas transmission system is performed and the maximum quantity of injectable hydrogen in each node is calculated to achieve a maximum limit of 10%. Of course, the thermo-physical properties of the new mixture, as well as the pressure drop in the network, are analysed.

In the paper [30], the potential of low percentage green hydrogen blending into the natural gas network is assessed. The results of this work show that at this moment, it is feasible to inject 715,000 Sm3/year into the current natural gas network by appropriately siting and sizing P2H (Power-to-Hydrogen) plants. However, strategies like natural gas network revamping or end-users adaptation are needed in order to reach the ambitious goals of the EU hydrogen strategy.

The effects of hydrogen blending in natural gas are also analysed in the paper [31], from an energetic point of view. The focus of this work is, in fact, on examining the reduction in transferable energy content when hydrogen is injected into the gas transmission network, while maintaining identical operating conditions. The authors of this paper define a new relative indicator, the transmissible energy factor (TEF) that quantifies the transmissible energy change from the case with pure natural gas.

Another paper that focuses on the analysis of the blending between natural gas and hydrogen is [32]. This work is about the simulation of the injection of pure hydrogen in an horizontal T-junction pipeline carrying natural gas, the aim is to study the mix of the two gases from a material-degradation point of view. In conclusion, the authors found out that the penetration of hydrogen molecules into natural gas is limited, therefore there is a high concentration of hydrogen in specific points of the T-junction that will be more exposed to embrittlement. Moreover, to ensure that the same amount of energy is delivered to the user, the flow rate in the junction has to be increased and this leads to a higher risk of fatigue failure.

A very recent paper is [33], here the authors investigate the potential of an hydrogen network that reuses existing gas network in order to balance the power oscillation that comes with the variation in wind and solar generation. The analysis shows that an hydrogen network could reduce the costs of the energy system especially when the expansion of the power grid is restricted.

This work aims to develop and evaluate a steady-state German gas transmission network simulation model using only open-source datasets and tools. Another aim of this thesis is to simulate green hydrogen blending into the German gas transmission network, and all the papers mentioned above highlight problems that arise when this molecule is blended into natural gas. The actual German regulations already allow a 10% hydrogen blend in natural gas [34]. However in this work, in order to take into account possible future scenarios in which hydrogen blending in natural gas is enhanced, the maximum percentage of hydrogen blended into natural gas is 20%.

To start the model of this transmission network, open source topology data are needed. The `SciGRID_gas` model project creates open-source datasets for the European gas transmission network, based on different data sources. It contains data about the gas network nodes, the pipelines between them along with compressors, storage and LNG terminals, and so on [35].

Regarding the demand data, `DemandRegio` (FZJ, TUB) and the German Network Agency (German: Bundesnetzagentur) datasets have been used. `DemandRegio` provides temporal and spatial disaggregation of the demands of natural gas, heat and electricity for the sectors of private households, commerce, trade and services (CTS) and industry. This dataset has been used to assign a demand to the nodes in Germany. On the other end, to take into account the exchange of natural gas with the neighbouring countries and to assign a demand to nodes outside of the country, Bundesnetzagentur data have been used. It provides data and charts for daily cress-border natural gas flow between the neighbouring European countries.

There are several software and tools available that are capable of analysing the hydrogen-enriched natural gas network. In this work, `GasNetSim` is chosen to perform the gas network simulation, which is an open-source, newly-developed tool that can perform gas network steady-state simulations. One highlight of this tool is the capability to study the behaviour of the network with different gas mixture compositions, for example, to simulate a natural gas network with hydrogen injection [36].

In the following chapters, the related mathematical models used for gas network steady-state simulation are first presented. Then, the datasets used for the modelling of the German gas transmission grid are presented and discussed. Afterwards, several scenario analyses are performed to illustrate the significance and the necessity of this work. At the end of this thesis, the simulation results are discussed and evaluated.

Chapter 2

Mathematical Formulation for the Modelling and Simulation of Gas Grids

2.1 Modelling of a gas pipeline

2.1.1 Importance of the gas pipeline infrastructure

Natural gas as a natural resource is usually directly found in populated and industrial areas where it is most needed [37]. Therefore it has to be moved from national and international extraction or, in the case of SNG, production sites to regional settlements by appropriate means of transport. For this purpose, pipelines have proven to be the optimal mechanism: they are more efficient at transferring vast quantities of natural gas than conventional shipments by rail, truck, or ships [38] and they create fewer GHG emissions than ship, truck or train [37].

In particular, in the case of Germany, the natural gas transport system covers the chain from production to consumption via transport and storage. The pipeline infrastructure system can be divided into four groups, depending on whether they are transmission or distribution pipelines: the long-distance, supra-regional, regional and local transport [39].

The German TSOs employ a total of around 40,000 km long-distance transmission network pipelines for trans-regional and cross-border natural gas transport. They enable links to connected transport networks, distribution networks, large industrial customers, gas power plants and underground storage facilities.

Hence, this transmission grid shapes the backbone of the German gas transport system while this country also has a regional and local distribution network for natural gas with a length of more than 470,000 km [40].

Large pipelines with a diameter up to 140 cm transport large quantities of gas. At high pressure (up to 100 bar), natural gas reaches Germany especially from Norway and the Netherlands over long distances. Besides, Germany also enables the transit of natural gas to neighbouring countries. Since the pipelines are very long, compressor stations are needed in order to compensate for pressure losses along them. Compression stations are placed with intervals between 100 and 200 km to ensure that the pressure remains stable over these long distances [40].

The downstream networks operated by the distribution system operators are connected to the main transmission network and ensure gas supply to end users in homes and businesses.

2.1.2 Steady-state gas pipeline model

A gas network usually consists of many different equipment, including pipelines, compression stations, plants over the line (equipment that controls the interconnections between pipelines and manages the pressure and flow rate of the system) and points on the line (ancillary installations line monitoring equipment and PIG stations), and so on. Among all these equipment, the pipeline is the dominant component. Therefore, the pipeline modelling is explained in detail in this section.

The compressible gas flow in pipelines is described by a set of equations expressing mass and momentum conservation laws, the one-dimensional isothermal Euler equations [41].

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial x} = 0 \tag{2.1}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v^2}{\partial x} + \frac{\partial p}{\partial x} + f\frac{v|v|}{2D}\rho + \rho g sin\theta = 0 \tag{2.2}$$

In the steady-state case, the time derivatives are null. Moreover, the velocity v and the gas mixture density ρ can be supposed to be constant along the pipeline. Therefore, Eq. 2.1 does not need to be considered anymore and the Eq. 2.2 becomes:

$$\frac{\mathrm{d}p}{\mathrm{d}x} + f\frac{v|v|}{2D}\rho + \rho g sin\theta = 0 \tag{2.3}$$

For a matter of convenience, instead of using density and velocity, Eq. 2.3 can be rewritten in terms of pressure and volumetric flow rate respectively, which are commonly measured and used in the gas industry.

$$v = \frac{Q}{A} \tag{2.4}$$

$$\rho = \frac{pM}{RTZ} \tag{2.5}$$

Therefore, equation 2.3 becomes:

$$\frac{\mathrm{d}p}{\mathrm{d}x} + \frac{f}{2DA^2}\frac{pM}{RTZ}Q|Q| + \frac{pM}{RTZ}gsin\theta = 0 \tag{2.6}$$

Moreover, in the gas industry, the volumetric gas flow rate is usually converted into the equivalent gas flow rate under the standard condition defined by the national government or the gas network operator, e.g. in Germany the standard condition is 15 °C and 1 atm. By integrating the previous ordinary differential equation by means of variables splitting, it is possible to obtain an expression for the volumetric flow rate along the pipeline:

$$Q = \pm\pi\sqrt{\frac{R}{16M_{air}}}\frac{T_{st}}{p_{st}}D^{2.5}\sqrt{\frac{|p_i^2 - p_j^2 - 2gsin\theta L\frac{p_{avg}^2 dM_{air}}{Z_{avg}RT_{avg}}|}{LdT_{avg}Z_{avg}f}} \tag{2.7}$$

To further simplify the equation, we can wrap up all constants and the pipeline parameters to define the pipeline coefficient as:

$$C_{pipe} = \pm\pi\sqrt{\frac{R}{16M_{air}}}\frac{T_{st}}{p_{st}}D^{2.5} \tag{2.8}$$

Therefore, Eq. 2.7 can be rewritten as:

$$Q = C_{pipe}\sqrt{\frac{|p_i^2 - p_j^2 - 2gsin\theta L\frac{p_{avg}^2 dM_{air}}{Z_{avg}RT_{avg}}|}{LdT_{avg}Z_{avg}f}} \tag{2.9}$$

Where p_i is the pipeline inlet pressure and p_j is the pipeline outlet pressure. The flow rate can enter or exit the pipe, as shown in figure 2.1.

The possible cases are two:

- $p_i - p_j > 0 \Rightarrow p_i > p_j$
- $p_i - p_j < 0 \Rightarrow p_i < p_j$

In the first case, the flow rate enters the pipeline from section 2 and exits from section 1, while the contrary happens in the second case.

What is left to determine is the friction factor f, the compressibility factor Z and the specific gravity d, both of them can be calculated in many ways.

Regarding the friction factor, in case of turbulent flow (Re > 4000) it can be calculated with the Colebrook-White equation in its implicit form [42]:

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{2.51}{Re\sqrt{f}} + \frac{\epsilon}{3.71D}\right) \tag{2.10}$$

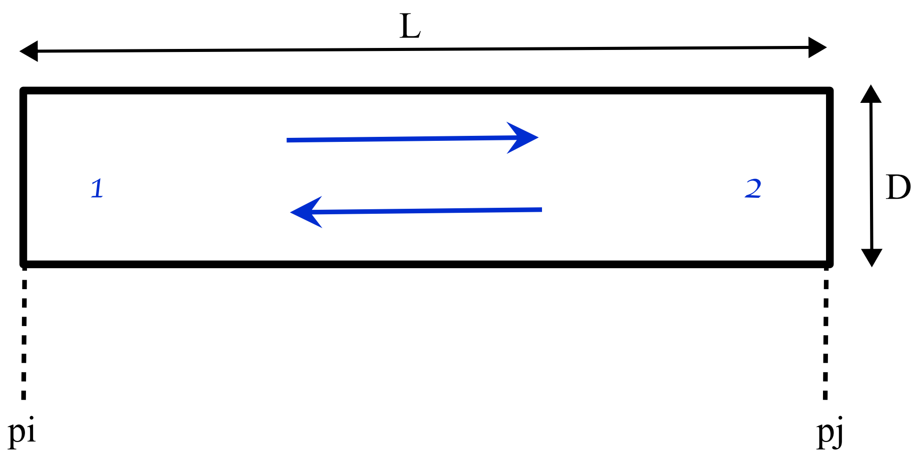

Figure 2.1: Flow rate in single pipeline

The Colebrook-White equation tends to calculate a higher friction factor, hence it is conservative [42]. This nonlinear equation can be re-written to be solved by a method of successive substitution or the Newton-Raphson method can be used for the same purpose. Alternatively, it is possible to use an explicit equation that is accurate enough to directly obtain the value of the friction factor f. Some examples of explicit equations are:

- Moody

$$f = 0.0055\left(1 + \left(2 \times 10^4 \frac{\epsilon}{D} + \frac{10^6}{Re}\right)^{\frac{1}{3}}\right) \tag{2.11}$$

  According to the author, this equation is valid for Re ranging from 4000 to 10^8 and values of ϵ/D ranging from 0 to 0.01 [43].

- Chen

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\epsilon/D}{3.7065} - \frac{5.0452}{Re}\right) \times log_{10}\left(\frac{(\epsilon/D)^{1.1098}}{2.8257} + \frac{5.8506}{Re^{0.8981}}\right) \tag{2.12}$$

  This method involves carrying out two iterations of the Colebrook–White equation. The equation proposed by Chen is valid for Re ranging from 4000 to 4.108 and values of ϵ/D between 0.0000005 and 0.05 [43].

- Hofer

$$f = \left(-2log_{10}\left(\frac{4.518}{Re}log_{10}\left(\frac{Re}{7}\right) + \frac{k}{3.71D}\right)\right)^{-2} \tag{2.13}$$

This method is of sufficient accuracy for transient gas network simulations [25].

- Manadilli

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\epsilon/D}{3.70} + \frac{95}{Re^{0.983}} - \frac{96.82}{Re}\right) \tag{2.14}$$

  The author, using what he calls signomial-like equations, claims that the equation is valid for Re ranging from 5235 to 108, and for any value of ϵ/D [43].

According to [43], the best predictions are achieved with those equations obtained from two or three internal iterations of the Colebrook–White equation.

In terms of calculating the compressibility factor, there are two primary methods: correlation and equation of state [44].

When it comes to correlations, the key ones are as follows:

- Papay

$$Z = 1 - \left[\frac{3.53P_{pr}}{10^{0.9813T_{pr}}}\right] + \left[\frac{0.274P_{pr}^2}{10^{0.815T_{pr}}}\right] \tag{2.15}$$

  This is a simplified expression of compressibility factor as functions of pseudo-reduced temperature T_{pr} and pressure p_{pr}. This method is fairly accurate and reliable for predicting the gas compressibility factor [44].

- Beggs and Brill

$$Z = A + (1-A)EXP(-B) + CP_{pr}^D \tag{2.16}$$

  Where A, B, C and D are functions of the pseudo-reduced temperature and pressure. This is an explicit equation of state expressed as functions of the pseudo-reduced temperature and pressure. However, this method is not suitable if the pseudo-reduced pressure is less than 0.92 [44].

- Dranchuk-Abu-Kassem

$$Z = \left[\frac{0.27P_{pr}}{\rho_r T_{pr}}\right] \tag{2.17}$$

  This method uses eleven constant variables to calculate the reduced density ρ_r which generate the analytical expression. It is also developed thanks to pseudo-reduced temperature and pressure but it is only applicable in a small range of these variables [44].

With respect to the equations of state (EOS), the most widely used are:

- Hall-Yarborough equation of state

$$Z = \left[\frac{0.06125P_{pr}t}{Y}\right] EXP[-1.2(1-t)^2] \tag{2.18}$$

This method cannot be used if the pseudo reduce temperature is less than one [44].

- Virial equation of state

$$Z = 1 + \frac{BP}{RT} + \left[\frac{BP_c}{RT_c}\right]\left[\frac{P_r}{T_r}\right] \tag{2.19}$$

This correlation method has a moderately high degree of confidence level with little error encountered [44].

- GERG-2008 equation of state

This equation is an expanded version of the GERG-2004 equation [45]. GERG-2008 provides an explicit expression for the Helmholtz free energy as a function of density, temperature, and composition. This equation is established based on 21 natural gas components, it effectively covers various states such as gas phase, liquid phase, supercritical region, and vapour-liquid equilibrium states for mixtures containing these components, spanning the entire composition range. GERG-2008 is applicable within a normal validity range, encompassing temperatures from 90 to 450 K and pressures up to 35 MPa. It accurately represents the thermal and caloric properties using the most precise experimental data available within their respective accuracies. As well as the new equation, a comprehensive and user-friendly software package for the computation of many thermodynamic properties is developed [45].

In general, empirical correlation methods are easier to implement rather than the equation of state (EOS) method and the latter are more time-consuming. However, empirical methods typically exhibit limited validity across various gas mixtures, making them less effective when it comes to hydrogen injection, in which case is recommended to use equations of state [44].

2.1.3 Thermal Model

In order to determine the thermal behaviour of fluids in pipelines, the fundamental equation is the energy equation or first law of thermodynamics.

$$Q\frac{d}{dx}\left(h + \frac{v^2}{2}\right) + U_L(T - T_s) + Qgsin\theta = 0 \tag{2.20}$$

With the following hypothesis of:

1. Negligible kinetic term
2. Horizontal pipeline

3. Gas behaves accordingly to the virial equation of state

the equation 2.20 becomes:

$$Q\frac{dh}{dx} + U_L(T - T_s) + Qgsin\theta = 0 \tag{2.21}$$

At this point, it is possible to write an expression for the enthalpy, according to the analytical model developed by Chaczykowski and Osiadacz [46]. In this model enthalpy is described as a function of pressure and temperature:

$$dh = \left(\frac{\partial h}{\partial T}\right)_p dT + \left(\frac{\partial h}{\partial p}\right)_T dp \tag{2.22}$$

Further modifications to the expression above can be carried out. For example, the partial derivative of enthalpy with respect to pressure can be written as:

$$\left(\frac{\partial h}{\partial p}\right)_T dp = -\left(\frac{\partial T}{\partial p}\right)_h \left(\frac{\partial h}{\partial T}\right)_p \tag{2.23}$$

By definition, we have that:

$$\left(\frac{\partial T}{\partial p}\right)_h = \mu_{JT} \tag{2.24}$$

And that:

$$\left(\frac{\partial h}{\partial T}\right)_p = c_p \tag{2.25}$$

Where expressions 2.24 and 2.25 represent, respectively, the Joule-Thomson coefficient and the specific heat at constant pressure.

At this point, equation 2.21 can be rewritten as:

$$\frac{\mathrm{d}T}{\mathrm{d}x} - \mu_{JT}\frac{\mathrm{d}p}{\mathrm{d}x} + \frac{U_L}{Qc_p}(T - T_S) = 0 \tag{2.26}$$

Another fundamental equation is the momentum conservation equation 2.6. With the hypothesis of horizontal pipeline it can be written as:

$$\frac{\mathrm{d}p}{\mathrm{d}x} + \frac{f}{2DA^2}\frac{pM}{RTZ}Q|Q| = 0 \tag{2.27}$$

Therefore, the equation 2.26 becomes:

$$\frac{\mathrm{d}T}{\mathrm{d}x} - \mu_{JT}\frac{f}{2D}\frac{ZRQ|Q|}{pA^2}T + \frac{U_L}{Qc_p}(T - T_S) = 0 \tag{2.28}$$

Writing that:

- $\gamma = \mu_{JT} \frac{f}{2D} \frac{ZRQ|Q|}{pA^2}$
- $\beta = \frac{U_L}{Qc_p}$

A simple first order differential equation for the temperature is obtained:

$$\frac{\mathrm{d}T}{\mathrm{d}x} - \gamma T + \beta(T - T_S) = 0 \tag{2.29}$$

The previous ODE can be easily solved by variable separation. Integrating along one pipeline we obtain:

$$T_j = \frac{\beta}{\beta - \gamma} T_S (1 - e^{L(\gamma-\beta)}) + T_i e^{L(\gamma-\beta)} \tag{2.30}$$

Where T_j is the temperature of the gas exiting the pipeline, T_i is the temperature of the gas entering the pipeline and T_S is the temperature of the soil with which the pipeline is exchanging heat.

2.2 Simulation solution methods for gas network simulations

2.2.1 Overview of simulation solution methods

The first methods for solving pipeline network problems were presented by Hardy Cross in 1936 [47]. In his paper, he proposes two methods of analysis called "Method of Balancing Heads" and "Method of Balancing Flow". In the former method, the flow in the pipes of the network has always to satisfy the condition that the total flow into and out of each junction is zero, while in the latter the total change of head around each circuit always equals zero. The two methods could also be combined, but unfortunately the convergence was often slow or even non-existent in some cases [47].

Nowadays, the most important algorithms for pipe networks are usually divided into three categories: loop, element and node [48].

Loop-solving equations methods require less computer storage with respect to the others, but the initial flow must satisfy the continuity equation. Element-solving equation methods converge very fast and it is not necessary that the initial flow satisfies continuity, however they require more computer storage. Regarding instead the node-solving equations methods, they require less computational storage and they are more flexible in the sense that they can work with mixed boundary conditions (pressure and flow). A drawback of this method is its unreliability which comes from its sensitivity to the initial pressure and its inability to work with low resistance lines.

Two of the most well-known node methods approaches are the SIMPLE algorithm, developed by Patankar and Spalding [49] and the Newton-Raphson algorithm [50]. The original SIMPLE algorithm applies to incompressible flow but it can be extended to work with compressible flow as well. On the other end, the Newton-Raphson method is a simultaneous node method, which means that the flows are adjusted simultaneously and this improves the convergence [50]. In the work by Grewenstein and Laurie [48] it is shown that for incompressible flow, these two methods are nearly identical, in fact their mathematical formulation is the same.

2.2.2 The Newton-Raphson method

As previously stated, the Newton-Raphson method is used to solve non-linear systems of equations. It is a root-finding algorithm that starts with an initial guess, then it estimates the function with its tangent line and finally computes the intercept of this line with the x-axis, as it is shown in figure 2.2. This intercept is generally nearer to the root of the function than the initial guess and the method can be iterated until a satisfying solution is reached, i.e. until the required tolerance is reached.

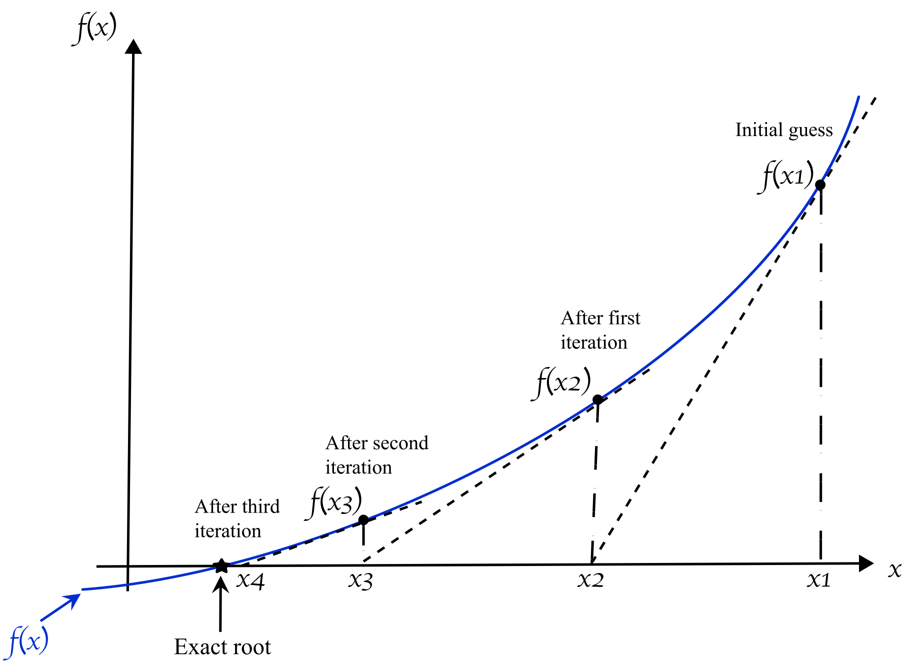

Figure 2.2: Convergence of Newton-Raphson algorithm

Let us represent the system with the following N equations:

$$\begin{matrix} f_1(x_1, x_2, \ldots, x_N) \\ f_2(x_1, x_2, \ldots, x_N) \\ \vdots \\ f_N(x_1, x_2, \ldots, x_N) \end{matrix} = \begin{matrix} 0 \\ 0 \\ \vdots \\ 0 \end{matrix} \tag{2.31}$$

If the components of one iteration $x^{(i)} \in \mathbb{R}^n$ are known, the above equations (2.31) can be written by using the Taylor expansion:

$$\begin{aligned} f_1(x_1^{(i+1)}, x_2^{(i+1)}, \ldots, x_N^{(i+1)}) \simeq f_1(x_1^{(i)}, x_2^{(i)}, \ldots, x_N^{(i)}) + \tfrac{\partial f_1}{\partial x_1}(x_1^{(i+1)} - x_1^{(i)}) + \\ + \cdots + \tfrac{\partial f_1}{\partial x_N}(x_N^{(i+1)} - x_N^{(i)}) \\ \vdots \\ \vdots \\ f_n(x_1^{(i+1)}, x_2^{(i+1)}, \ldots, x_N^{(i+1)}) \simeq f_n(x_1^{(i)}, x_2^{(i)}, \ldots, x_N^{(i)}) + \tfrac{\partial f_n}{\partial x_1}(x_1^{(i+1)} - x_1^{(i)}) + \\ + \cdots + \tfrac{\partial f_n}{\partial x_N}(x_N^{(i+1)} - x_N^{(i)}) \end{aligned} \tag{2.32}$$

Using a matrix form, the equations (2.32) can be rewritten as follow:

$$\begin{bmatrix} f_1(x^{(i+1)}) \\ f_2(x^{(i+1)}) \\ \vdots \\ f_N(x^{(i+1)}) \end{bmatrix} = \begin{bmatrix} f_1(x^{(i)}) \\ f_2(x^{(i)}) \\ \vdots \\ f_N(x^{(i)}) \end{bmatrix} + \begin{bmatrix} \frac{\partial f_1}{\partial x_1}|_{x^{(i)}} & \frac{\partial f_1}{\partial x_2}|_{x^{(i)}} & \cdots & \frac{\partial f_1}{\partial x_N}|_{x^{(i)}} \\ \frac{\partial f_2}{\partial x_1}|_{x^{(i)}} & \frac{\partial f_2}{\partial x_2}|_{x^{(i)}} & \cdots & \frac{\partial f_2}{\partial x_N}|_{x^{(i)}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial f_N}{\partial x_1}|_{x^{(i)}} & \frac{\partial f_N}{\partial x_2}|_{x^{(i)}} & \cdots & \frac{\partial f_N}{\partial x_N}|_{x^{(i)}} \end{bmatrix} \begin{bmatrix} (x_1^{(i+1)} - x_1^{(i)}) \\ (x_2^{(i+1)} - x_2^{(i)}) \\ \vdots \\ (x_N^{(i+1)} - x_N^{(i)}) \end{bmatrix} \tag{2.33}$$

Then, keeping into account the equations (2.31) into (2.33) and using a compact form where $K_{ab} = \frac{\partial f_a}{\partial x_b}|_{x^{(i)}}$:

$$J \Delta x = -f \tag{2.34}$$

where J is referred to as the Jacobean and it is an n x n matrix, f and Δx are vectors of n components.
If J is invertible, then, the above system can be solved as follows:

$$\Delta x = -J^{-1} \cdot f \tag{2.35}$$

From the above equation (2.35) the update variables can be computed:

$$x^{(i+1)} = x^{(i)} + \Delta x \tag{2.36}$$

The process is repeated until functions f are lower than the user-defined tolerance. The Jacobian has to be calculated at each step.

2.3 About GasNetSim

2.3.1 Overview of the tool

GasNetSim is a relatively newly developed tool for the gas network steady-state simulation [36]. This tool is open-source, therefore users have the flexibility to modify it and implement their own preferred gas mixture modelling approaches.

According to the authors, the tool can effectively simulate the gas network using different gas mixtures, allowing for precise analysis of the effects of hydrogen injection on the gas network. This is accomplished by iteratively calculating and updating the properties of the gas mixture throughout the simulation, taking into account its physical states and composition.

GasNetSim enables the users to perform steady-state natural gas network simulations with the option to calculate the temperature at the same time. Additionally, the simulation module also provides quasi-dynamic simulation based on time series. This feature is particularly useful to keep track of the chemical composition of the fuel transported during time, in fact it allows the user to know the exact chemical composition of the mixture at each time step [36].

2.3.2 Gas network modelling

The simulated network components are:

1. Node: here the the mass conservation law is employed in order to ensure a more precise equilibrium at the nodal level. Furthermore, the network nodes are categorised into three types based on their functionalities:

    - Reference nodes: these nodes have predetermined pressure and temperature values for the gas mixture. During the simulation, the flow rates at the reference nodes are computed to achieve a balance between the total gas supply and demand in the network. It's important to note that a gas network model may have multiple reference nodes.
    - Supply or demand nodes: these nodes are directly connected to sources or sinks in the network, representing points where gas is supplied or consumed.
    - Junction nodes: these nodes are not directly connected to any source or sink. They serve as intermediate points within the network.

2. Source and Sink: the supply and demand nodes establish direct connections with the sources and sinks, determining the flows associated with them. The flow rates can be characterised either as energy flow rate or volumetric flow rate, depending on the specific requirements. When considering the blending of

hydrogen into the natural gas network, it is more suitable to utilise the energy flow rate, this choice is justified by the fact that in real-world operations, it is essential to ensure that the energy demand is adequately met.

3. Pipeline and components resembling them: the model of the pipeline is extensively described in 2.1.2. In this tool different friction factor calculation methods are implemented, however the Chen friction model is set as the default. Regarding the compressibility factor, the GERG-2008 EOS is implemented, it is an EOS method developed specifically for natural gas The fictitious components are represented by short pipes or fictitious resistance, the state variables of these components are determined using a similar calculation approach as that employed for conventional pipelines within the simulation.

4. Valve: it regulates the connection between two distinct network nodes by operating in two distinct states: open and closed.

5. Compressor: it is represented using a simplified model based on the compression ratio. Additionally, the power consumption of the compressor station is incorporated into the simulation to account for the coupled power and gas systems.

2.3.3 Simulation

The simulation is solved using the Newton-Raphson method, extensively discussed in 2.2.2, according to the solution flow shown in 2.3. This method does not support the flat-start initialisation, therefore it is not possible to assume the initial pressure at all the nodes to be the same. Based on experience, pipeline outlet pressures are initialised at approximately 0.98 of the inlet pressures. In order to perform this, a straightforward algorithm is employed to set the initial pipeline outlet pressures, this algorithm begins from the reference nodes and progressively assigns pressure values to each node until all nodes have a pressure value. This process also guarantees that nodes directly connected via a pipeline cannot have identical pressure values.

During each iteration step, the Jacobian matrix is updated, enabling the calculation and update of the state variables. The program continues iterating as long as the error between the calculated and target values after an iteration step exceeds the specified tolerance. Throughout this process, node pressures are adjusted and pipeline properties are simultaneously updated. Once the error falls below the set tolerance, signifying convergence, the simulation is considered complete, and the results are saved.

For more information about the details of the tool, please refer to [36].

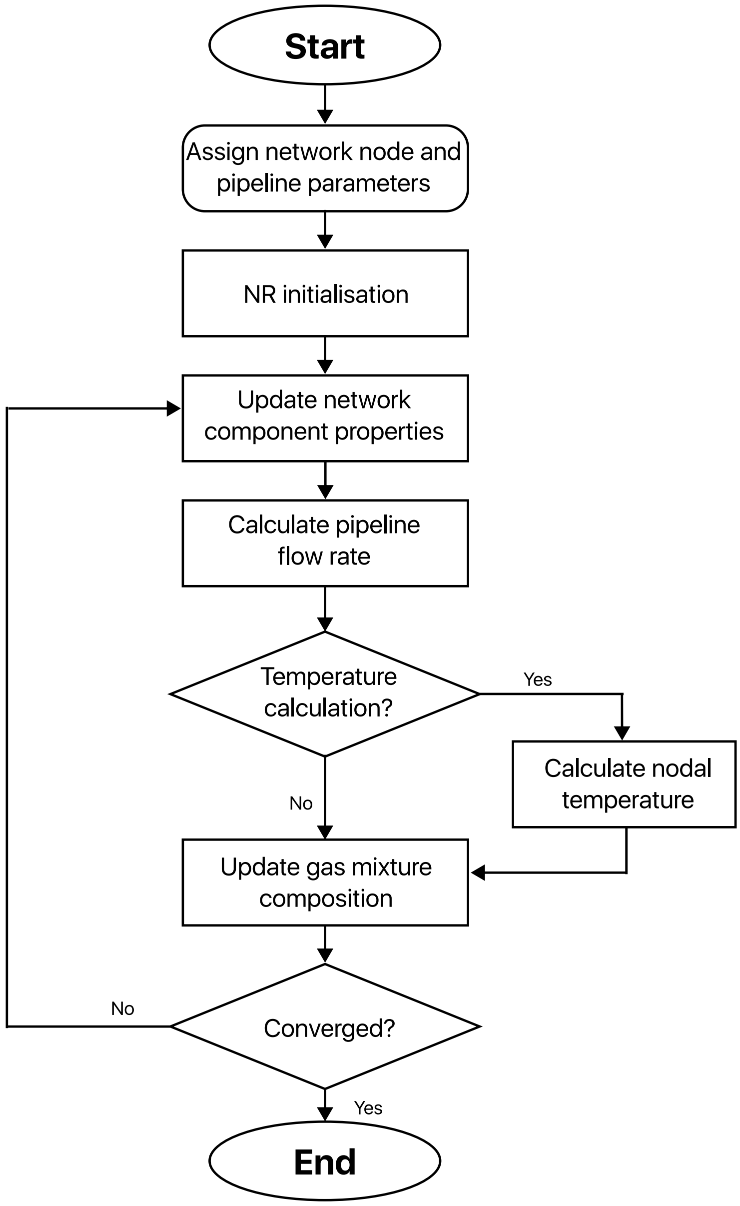

Figure 2.3: `GasNetSim` simulation solution flow

Chapter 3

Datasets used for the German Gas Transmission Grid Modelling

3.1 Topology Data

For the topology data, a dataset published under the `SciGRID_gas` project is used: `SciGRID_gas IGGIELGN` [51]. This dataset is generated based on several different open-source data sources for the European gas network, including:

- Internet dataset (INET)

  The dataset comprises geographical and meta-information regarding the European gas transport network. This data was gathered through extensive internet research, including Wikipedia, fact sheets from gas transmission system operators, maps, press releases, and other sources [52]. As a result, a significant portion of the data had to be manually extracted [51].

- Gas Infrastructure Europe dataset (GIE)

  Gas Infrastructure Europe (GIE) is the association of the gas infrastructure operators of Europe. The organization's endeavours are categorized into three main areas: GTE (transmission pipelines), GSE (storage facilities), and GLE (LNG terminals) [53].

- Gas Storages Europe dataset (GSE)

  The storage database is part of the previously mentioned Gas Infrastructure Europe dataset. In particular, it provides data about the operation of the storage facilities such as the storage facilities working gas volume, as well as their injection and withdrawal capacities, alongside the storage sites currently under construction and those planned for development [54].

- International Gas Union dataset (IGU)

  This dataset is provided by the International Gas Union, which boasts a membership exceeding 160 organizations worldwide. These members include both national gas industry associations and corporations. IGU's operational structure encompasses the entire gas industry value chain, spanning from upstream to downstream. IGU is dedicated to enhancing the quality of life by promoting gas as a pivotal contributor to a sustainable energy future [55].

- ENTSOG-map data set (EMAP)

  The ENTSOG-map data consists of a map supplied by ENTSOG which stands for European Network of Transmission System Operators for Gas. Its role is to facilitate and enhance cooperation between national gas transmission system operators (TSOs) across Europe [56]. The map includes gas pipelines, drilling platforms and storage facilities of all of Europe, including non-EU states [51].

- Long-term Planning and Short-term Optimization data set (LKD)

  This dataset was collaboratively created by multiple German research institutes and received funding through government grants in Germany [51]. This dataset encompasses valuable information regarding gas pipelines, gas production facilities, gas storage sites, compressor station locations, and network nodes [51].

- Great Britain data set (GB)

  The data for Great Britain come from the National Grid Group. National**grid** is the main TSO for the electricity and gas network in Great Britain, but it also covers the other regions of the United Kingdom. It provides facility data as well as instantaneous gas flow time series data [51].

- Norway data set (NO)

  The data for Norway are provided by their main operator Gassco [57]. Gassco allows the download of the geo-referenced gas and oil facility data [51].

In addition to the datasets mentioned above, gas network data available from the open-source geographical dataset OpenStreetMap (OSM) is used. They are freely available and provide accurate topological information about pipelines. However, they lack metadata, for example, the pipeline diameter. In order to estimate and supplement this missing data, the developers use heuristic processes, which are described in detail in [51].

The final `SciGRID_gas IGGIELGN` contains information about different gas network components, which are listed below:

- Nodes

  Network junctions or endpoints connecting the gas supply, demand or storage. Also, other network elements have an associated node, such as compression stations and power plants.

- Pipelines

  They enable the transfer of gas from one node to another and they are able to connect all the network elements.

- Pipe segments

  Very similar to pipelines, but they can only connect nodes.

- Compressors

  Compressor stations are able to increase the pressure of gas in order for it to flow to the successive node.

- LNGs

  They represent Liquefied Natural Gas (LNGs) terminals and storage.

- Storages

  Facilities that store the underground surplus of natural gas and deploy it during low supply or high demand periods.

- Consumers

  They represent the gas users.

- Production

  Gas extraction sites. Even if the majority of the gas consumed in Europe is sourced from countries beyond the EU borders, there are various smaller gas production facilities spread across different parts of Europe.

- Border points

  Represent measuring stations at the borders between countries.

- Entry points

  European Union's border points.

- Interconnection points

  These connection points serve as interfaces between gas transmission operators.

A complete picture of the German network generated based on the `SciGRID_gas IGGIELGN` dataset is shown in Figure 3.1

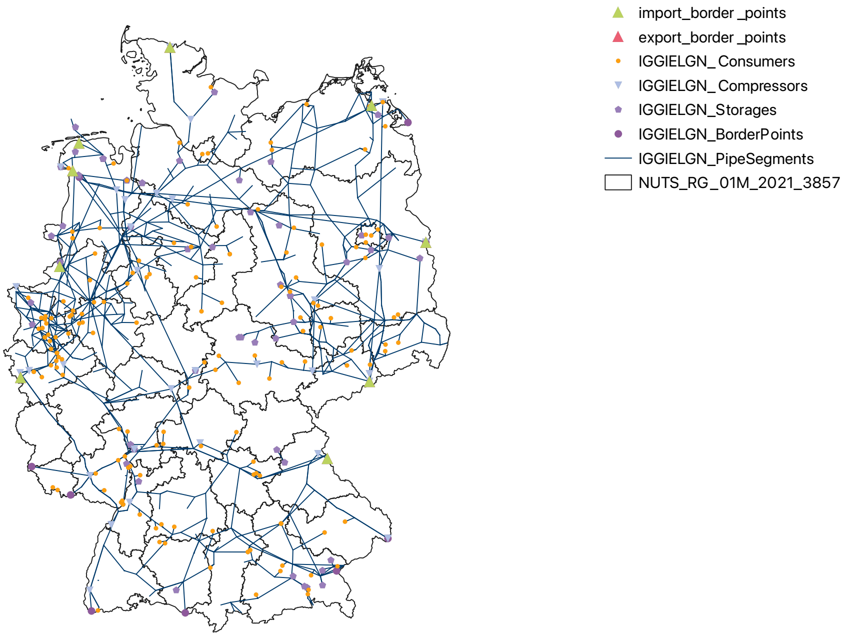

Figure 3.1: German gas network

Of particular interest for the gas network modelling is the data regarding pipelines and compressors.

With respect to the pipeline data, an attribute that needs attention is the flow direction. Broadly speaking, the dataset has been structured in a manner where gas typically moves from the initial to the final node of each pipeline. Nonetheless, for a considerable number of pipes, it remains uncertain whether this presumption holds true. Moreover, certain pipelines have the capability of bidirectional operation. Consequently, a heuristic technique has been established to ascertain the direction of gas flow, while the exact flow directions remain uncertain [51].

Regarding compressors, they are a vital part of the network in the sense that they increase the pressure of gas so that it flows in the right direction. Unfortunately, the data about the compressors is limited. The data provided only regards compressors located at the network nodes, while the data about compressors located in the pipelines, which usually is the larger share of the total compressors, are not provided because it was not possible to retrieve enough information [51]. Apart from topology data for compressors, it is crucial to know how they are operated. Unfortunately, the operational information of the compressors is not available as open-source. As a result, it is impossible to accurately model the compressor operation status in the simulation study. Therefore, the compressor data is not considered in the final simulation.

For the purpose of simulating the German gas transmission network, the data about pipelines and nodes are used. In particular, the data-cleaning procedure is the following:

1. Find the pipelines that have at least one end in Germany

   To have a complete picture of the German gas network, it is important to also consider the pipelines that start and end abroad, in order to take into account the gas flow with the neighbouring countries.

2. Select all the inlet and outlet nodes of these pipelines

   Every pipeline is characterized by an inlet and an outlet node, it is important to take all these nodes into account.

3. Find the reference nodes

   The reference nodes represent a boundary condition for our simulation, they are the "starting point" of the network. First, all the starting nodes of pipelines that start abroad and end in Germany are selected. It is important to point out that not all these nodes are reference nodes, the fact that they are located abroad does not directly mean that they are the starting point of the network. In fact, as already said in 3.2.2, ring flows are present. They refer to gas flow that leaves Germany at a border and is redirected back to Germany elsewhere. By taking into account only the nodes abroad that are not part of any ring flow and are actually the starting points of the network, 19 reference nodes are selected: 5 in the Netherlands, 5 in Poland, 3 in Norway, 2 in Switzerland, 2 in Austria, 1 in France and 1 in Denmark.

4. Remove the unrealistic pipelines

   In working with the dataset, some unrealistic values have been noticed, especially regarding the pipelines. In particular, for roughly fifty pipelines, the same node is listed as inlet and outlet, furthermore, the length of these pipelines is reported as zero kilometres. Since these data are considered to be not correct, they have been removed from the final dataset.

5. Remove the subnetworks

   Apart from the main network, about 10 smaller networks (composed of one, two or three pipelines with the respective nodes) are present in the data.

These subnetworks could be present because of a lack of data: for example, the pipeline that should connect the subnetwork to the main network is missing. Since the simulation needs a completely interconnected network in order to correctly function, these subnetworks have been removed.

The final topology dataset is then composed of 658 nodes and 1019 pipelines to represent the German gas transmission network, it is shown in Figure 3.2. Each node of the network needs to be assigned a demand of natural gas, the details about how this demand is provided are discussed in the following sections.

3.2 Demand Data

3.2.1 Domestic demand

In order to choose the proper dataset for the domestic demand of natural gas in Germany, two different datasets are compared and evaluated: `DemandRegio` [58] and `SciGRID_gas CONS` [59].

`DemandRegio` provides data and tools in order to spatially and temporally disaggregate the German electricity and gas demand. The results consist of three time series of demand, one for each analyzed sector, and they are provided with a NUTS-3 resolution every 15 minutes for the industrial sector and every hour for the households and CTS sectors.

The `SciGRID_gas` project aims to build an open-source dataset of the European Gas Transmission network. In particular, the `SciGRID_gas CONS` dataset is published within the framework of the `SciGRID_gas` project and provides synthetic gas demand data. The results consist of the daily gas consumption, broken down into industrial, residential and commercial, trade and services sectors, for all the NUTS-1, NUTS-2 or NUTS-3 regions of European countries.

In order to compare the two sets of data, the hourly data from `DemandRegio` are summed up in order to obtain daily data. The results of this comparison, for the year 2015, are shown in the figures below. First, the temporal disaggregation is shown.

For the industrial sector, shown in Figure 3.3 and 3.4, the disaggregation is based on the day of the week, in particular the difference of load between weekdays and weekends/holidays is highlighted.

It is possible to note that `DemandRegio` takes into account higher loads (between 85 and 65 Mm^3 per day), while `SciGRID_gas CONS` considers a lower demand (roughly between 62 and 48 Mm^3 per day).

Moreover, `DemandRegio` is more accurate regarding the consideration of public holidays, while `SciGRID_gas CONS` only accounts for holidays common for the whole country, `DemandRegio` considers the holidays for each Bundesland independently.

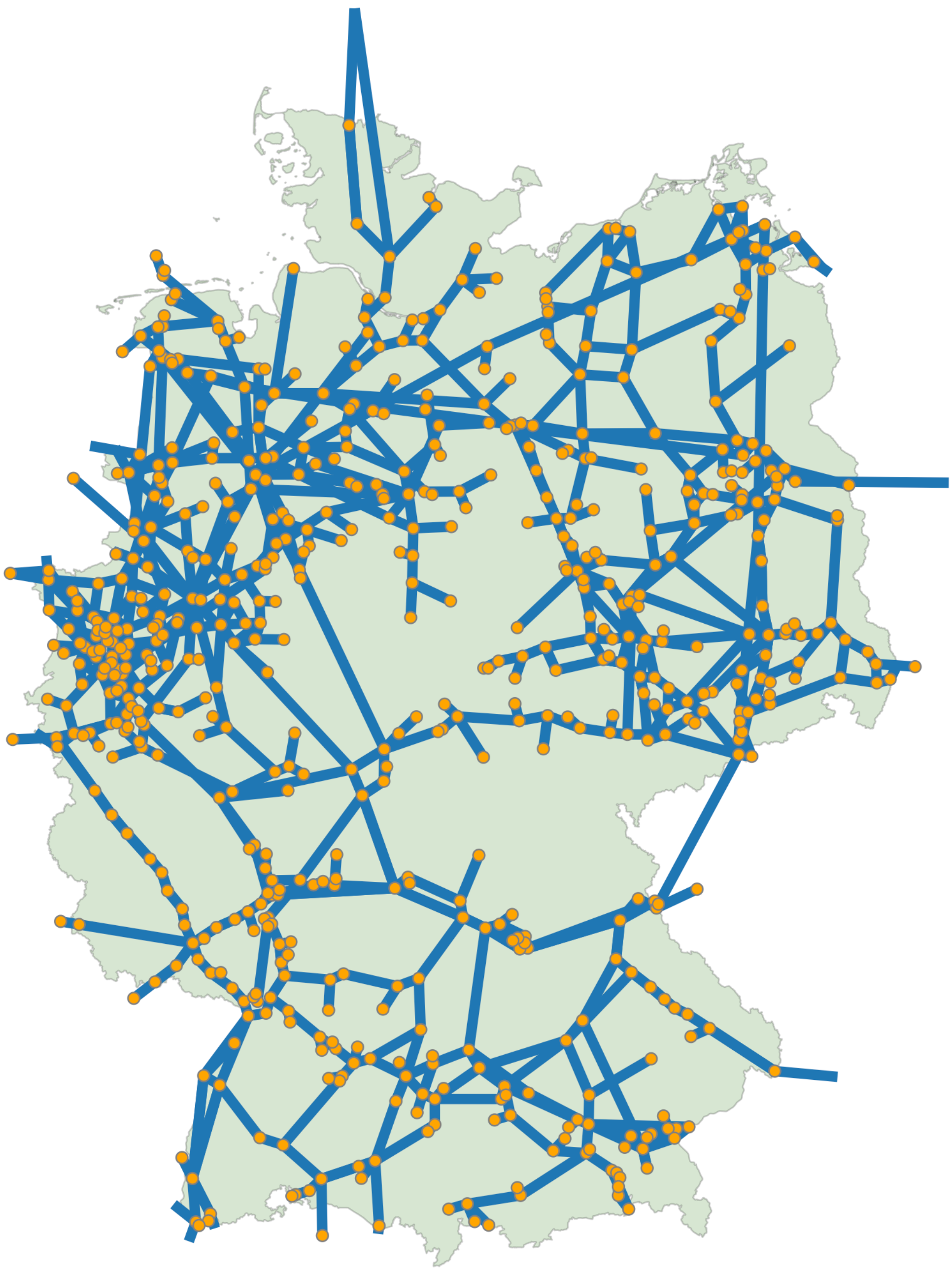

Figure 3.2: Model of the German gas transmission network

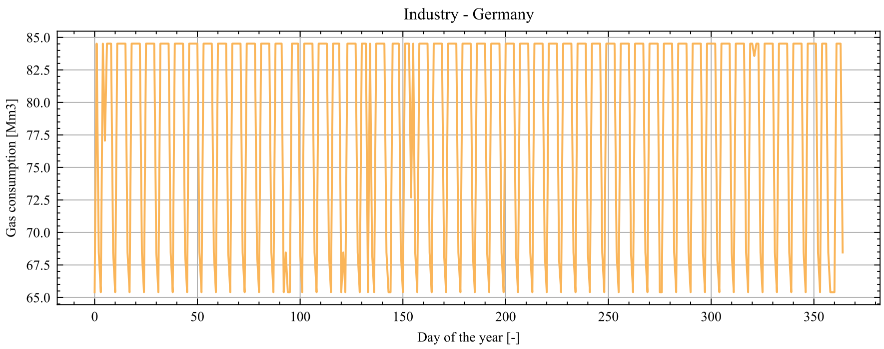

Figure 3.3: DemandRegio industry data

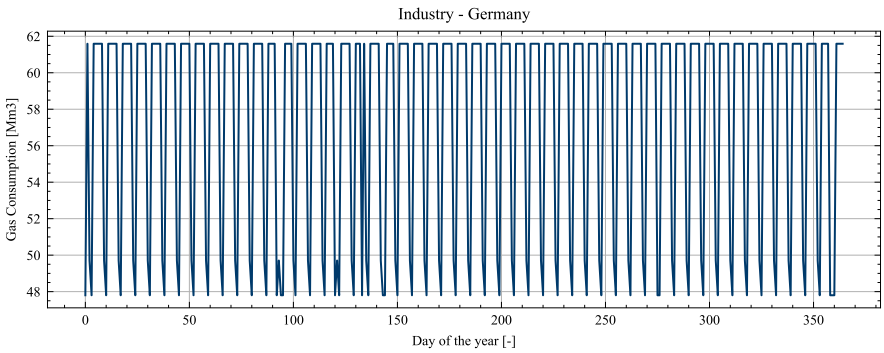

Figure 3.4: SciGRID_gas CONS industry data

That is why in Figure 3.3 some lower peaks of consumption are noticeable, these correspond to days like epiphany (the 6th of January), Pentecost (the 4th of June) or repentance day (18th of November), that are regional public holidays.

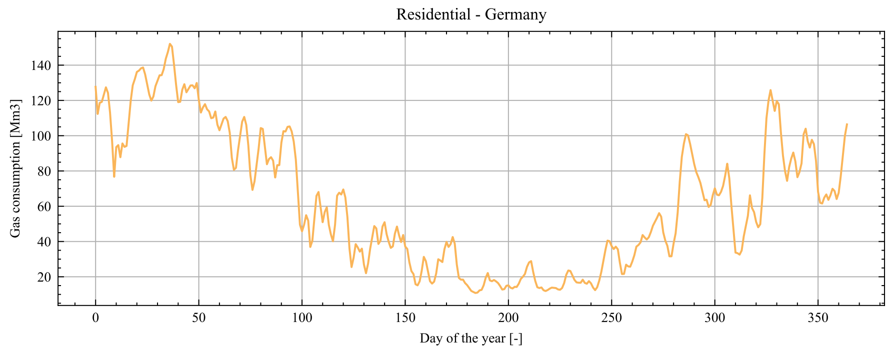

Figure 3.5: DemandRegio residential data

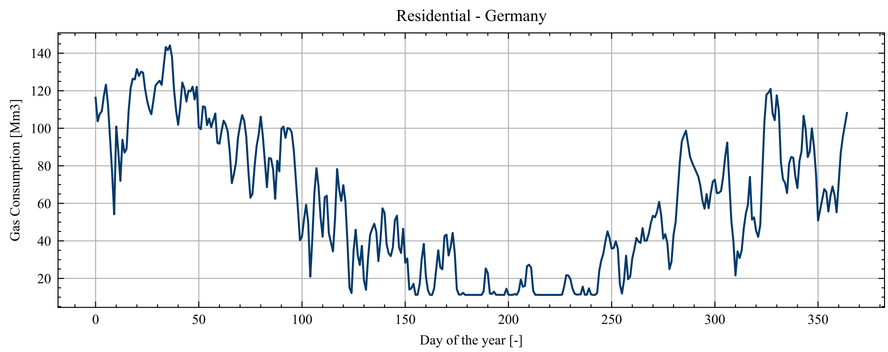

Figure 3.6: SciGRID_gas CONS residential data

Regarding instead the residential and commercial, trade and services (CTS) sectors, shown in Figure 3.5, 3.6, 3.7 and 3.8, the seasonal behaviour of the demand is evident. The values of the two datasets are more in accordance with respect to the industrial sector, even if the values provided by `DemandRegio` are always slightly higher.

The figures below show instead the spatial disaggregation for the same sectors.

Similar to the temporal disaggregation, there is also a significant difference between the two datasets in the spatial disaggregation for the industrial sector (see Figure 3.9 and 3.10). `DemandRegio` provides generally higher demand values than the ones from `SciGRID_gas CONS`. A possible explanation is that the former takes the raw material usage of natural gas for the industrial sector into account, while the latter does not.

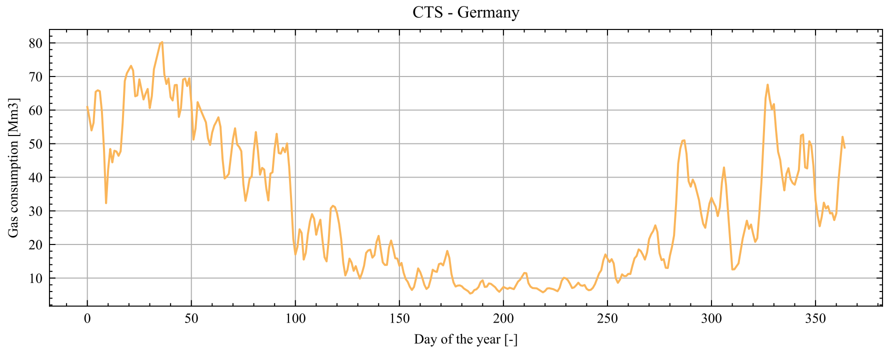

Figure 3.7: DemandRegio CTS data

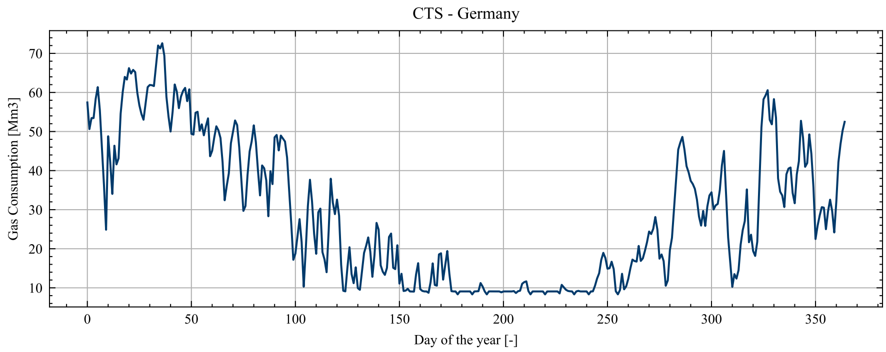

Figure 3.8: SciGRID_gas CONS CTS data

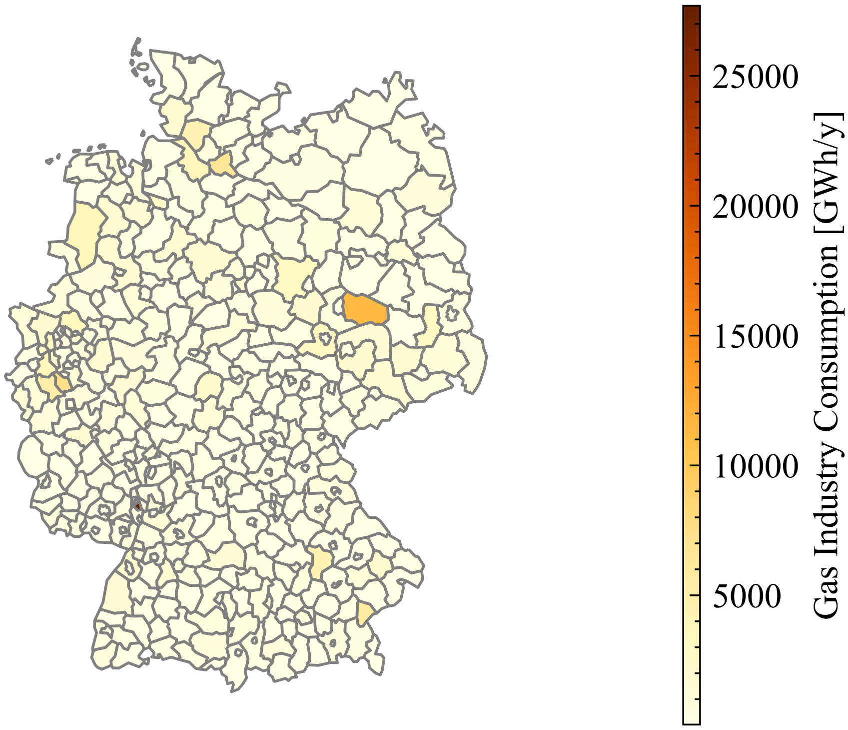

Figure 3.9: DemandRegio industry data

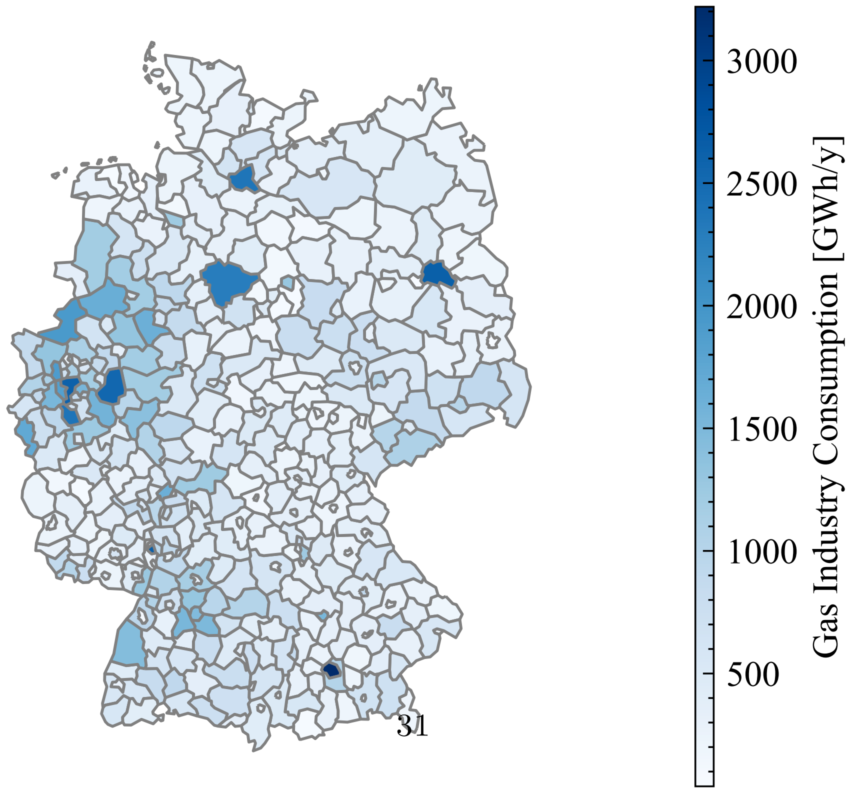

Figure 3.10: SciGRID_gas CONS industry data

It is worth noting that a peak demand can be observed in a very small region in the southwest part of the country. The percentage of the natural gas consumed in this region with respect to the whole nation is correspondingly 9.61% from `DemandRegio` and 1.2% from `SciGRID_gas CONS`. After some research, this region corresponds to the city Ludwigshafen am Rhein, where the chemical giant BASF SE is located. The chemical company has its own power plant that covers almost 60% of the total electricity it consumes, which is generated mainly from natural gas [60]. At the same time, the company also uses natural gas for its chemical products. Therefore, although the generated data from `DemandRegio` is quite high, it is believed to be more accurate, because the raw material usage of natural gas is taken into account.

Regarding residential and CTS sectors, shown in Figure 3.11, 3.12, 3.13 and 3.14, just as the temporal disaggregation, the values are very similar between the two datasets and the peaks of demand are located in the same districts.

The peculiarities of the two datasets are summarized in the table 3.2:

	`DemandRegio`	`SciGRID_gas CONS`
Electricity and gas demand	Yes	No
Non Energetic gas demand	Yes	No
European data	No	Yes
NUTS-3 resolution	Yes	Yes
Hourly resolution	Yes	No
Public holiday for Bundeslands	Yes	No

Table 3.1: Summary of the features of the two datasets

With respect to the features summarized above, it has been decided to work with `DemandRegio`, mainly because it takes into account the demand for non-energetic use of natural gas and because it provides hourly data. More details about this dataset are provided in the following paragraphs.

Regarding the spatial disaggregation, it follows the NUTS system (French: Nomenclature des unités territoriales statistiques). It refers to a hierarchical system consisting of four levels for the clear identification and classification of areas in the Member States of the European Union. The following applies to Germany:

- NUTS-0: National level, first two digits of the NUTS code (e.g. DE stands for Germany)

- NUTS-1: Federal state level, first three digits of the NUTS code (e.g. DEA stands for the federal state North Rhine-Westphalia)

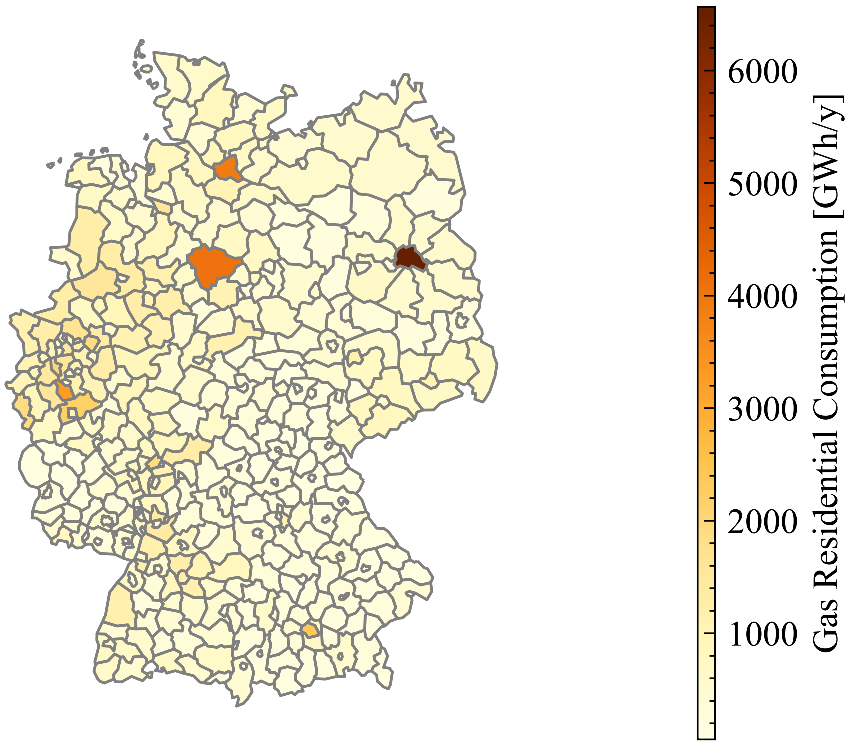

Figure 3.11: DemandRegio residential data

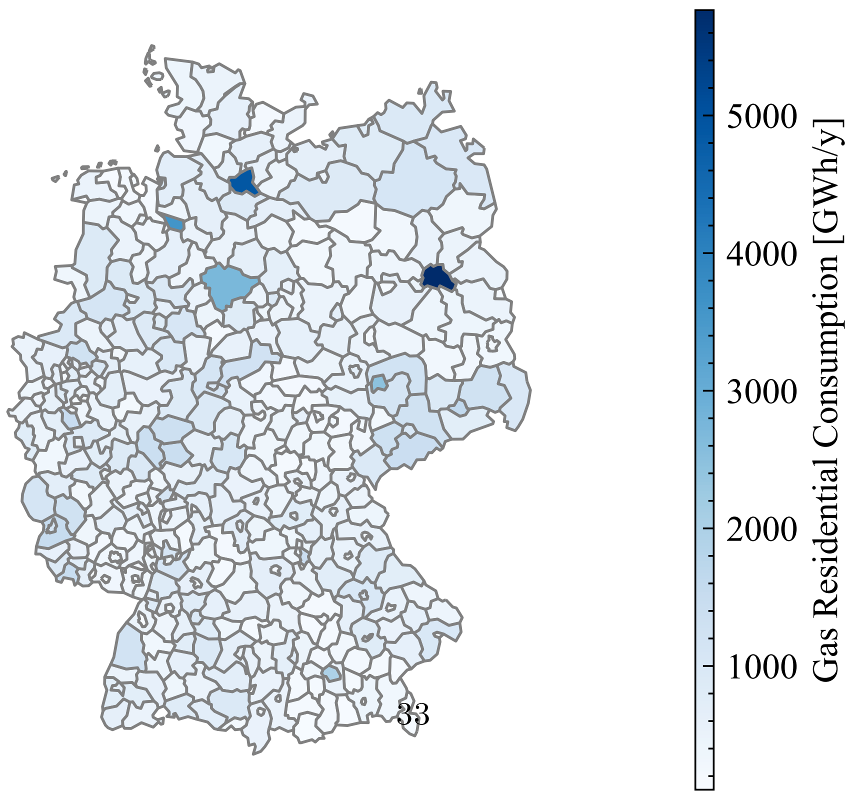

Figure 3.12: SciGRID_gas CONS residential data

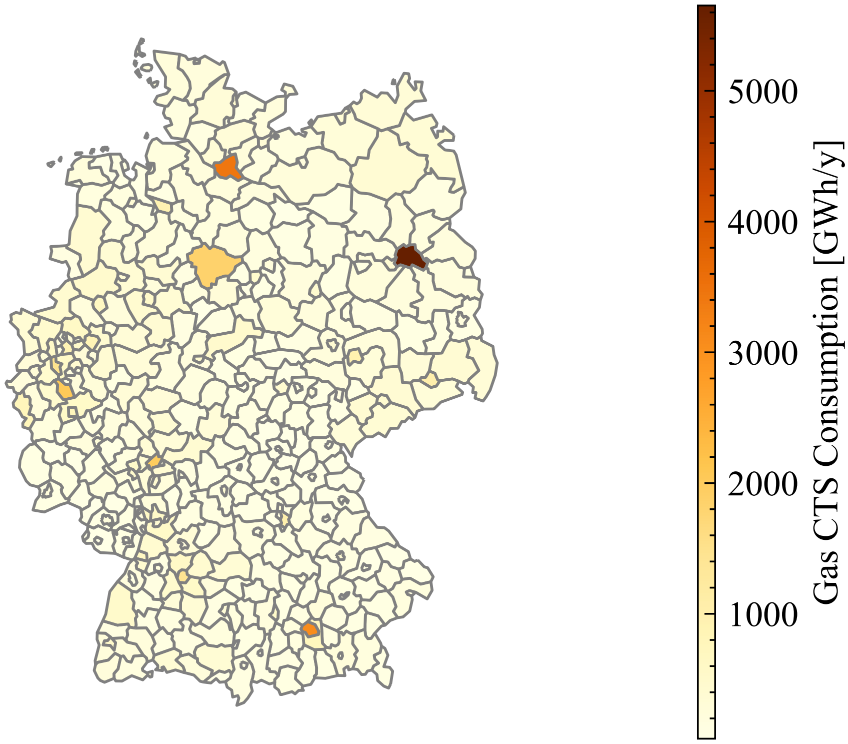

Figure 3.13: DemandRegio CTS data

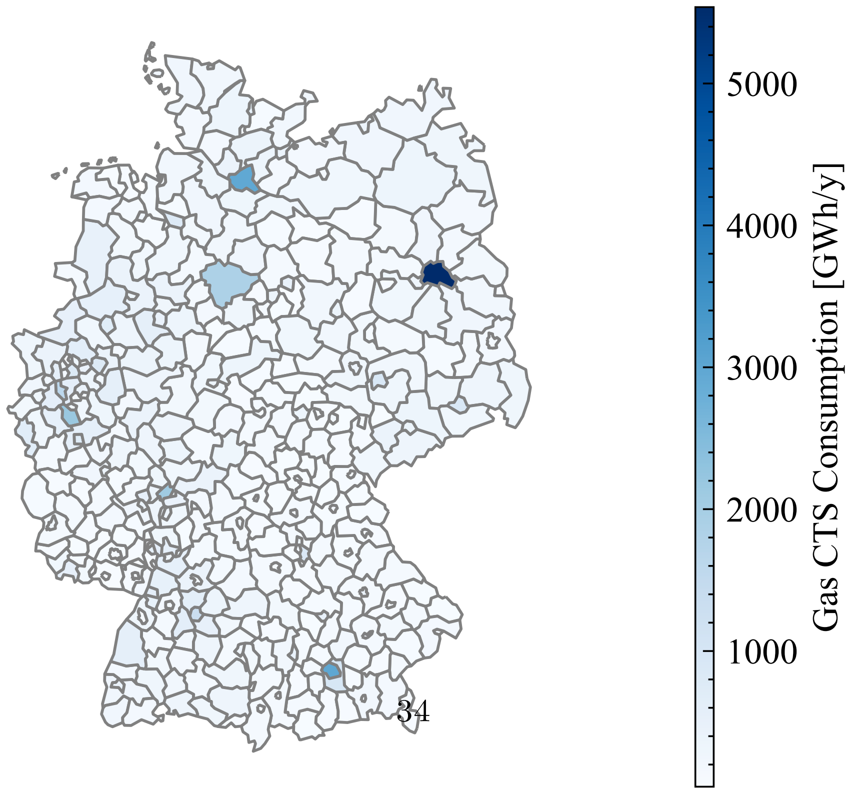

Figure 3.14: SciGRID_gas CONS CTS data

- NUTS-2: (former) administrative districts, first four digits of the NUTS code (e.g. DEA2 stands for the administrative district of Cologne)
- NUTS-3: Districts and cities without districts (=Landkreise), five digits of the NUTS code (e.g. DEA22 stands for the city of Bonn)

In the course of territorial reforms, however, there are always changes throughout Europe (for example, cities and/or districts merge, creating new areas and dissolving old ones). In the NUTS 2016 classification, that is currently valid, i.e. since the 1st of January 2018, and utilized in this dataset, there are 16 federal states (NUTS-1 regions), 38 administrative districts (NUTS-2 regions) and 401 districts and independent cities (NUTS-3 regions) in Germany [61].

The temporal resolution is understood as the smallest possible recurring time interval that can be described by means of model output. Typical temporal resolutions of energy system analytical models range from annual (low resolution) to daily to hourly (high resolution) and secondly (very high resolution) time intervals. Energy system models with a lower temporal resolution are typically associated with a long modelling horizon of several years or decades, whereas the temporal horizons of high-resolution energy system models are associated with much shorter time spans. The creation of high temporal resolution models in the `DemandRegio` research project is based on the time intervals of the registering power measurement, which are specified for the electricity and gas systems by the regulator. In `DemandRegio`, the electricity load is therefore mapped in quarter-hourly resolution and the gas load in hourly resolution.

Regarding the demand for private households, following the definition of the term by the Federal Statistical Office (Destatis) [62], the term “private household” is defined as a community of people who manage and live together - this also includes individual people living alone. The household size is defined as the number of household members according to the Destatis. However, only those groups of people who establish their own independent households are included in the category of private households. People who live together, e.g. in old people’s homes, hospitals, communal care or in public institutions, are accordingly not included. This separation serves to avoid double counting, as the electricity and gas requirements of hospitals, old people’s homes, barracks, etc. are directly allocated to the respective economic sectors.

The spatial resolution of the final energy demand of private households can be achieved on the one hand by either a bottom-up approach or a top-down approach. In the bottom-up approach, the regional electricity and gas demand is multiplied by the number of households per district on the basis of a specific energy consumption parameter from literature or statistics, e.g. electricity consumption per household. The quantities determined in this way for each district can then be aggregated and compared with regionally lower-resolution data. In contrast, in the top-down approach, the electricity and gas demand is distributed from an aggregated level (e.g. the static value from the energy balances of the federal government) to the county level on the basis of the reference objects. For this purpose, so-called distribution keys are first derived, usually as a share per district in the total sum of the energy demand determinants (ENaG) like weather data or calendar information, and then multiplied by the aggregated demand. Although these two approaches can use the same data, e.g. number of households per district, for spatial distribution, they can yield different results. The quality of the distribution thus depends on the one hand on the quality of the data on the spatial distribution and on the other hand on the specific or absolute initial value used.

Regarding the temporal disaggregation, three main methods have been used in `DemandRegio`:

1. Standard load profile procedure for electricity

   For private households (as well as other sectors such as agriculture and small to medium-sized businesses), there is no power metering. Instead, typified profiles are used here in quarter-hourly cycles, which indicate similar consumption behaviour. The so-called standard load profiles (SLP) were developed as early as 1999 on behalf of the German Electricity Industry Association [63]. Since then, this profile is mainly used by grid operators to distribute the annual load of electricity to individual time steps.

2. ZVE procedure for electricity

   A completely different approach than the recourse to and listing of predefined profiles is followed by the ZVE procedure. Here, activity-based load profiles are derived based on surveys of the electricity consumption of different applications per household size and the different activities of the household members in the course of the day as well as the basic loads that occur.

3. Standard load profile procedure for gas

   Analogous to the load profile for electricity demand, there is also a load profile for gas demand for private households [63]. Since the natural gas demand in Germany is strongly related to the provision of space heating, the outdoor temperature must also be taken into account. Furthermore, a distinction is made between single-family houses and multi-family houses. Since detached houses are less common than single-family houses, it is assumed that they emit less heat to the sides - due to the neighboring houses - and thus have a specifically lower average consumption. The calculation of the time series is based on SLPs for the gas sector and it is described in detail in [64]

Regarding the definition of the industrial and CTS sectors, the classification WZ 2008 of the Federal Statistical Office is used. Since the WZ 2008 classification includes both industrial and tertiary sectors, the distinction between these two sectors is made solely on the basis of the economic branches [63]. The classification according to WZ differs from the classification of the AGEB (which is a German energy market research group), which assigns all manufacturing and processing companies with fewer than 19 employees to the CTS sector and assigns larger manufacturing and processing companies to the industrial sector. The classification is based on the size of the company, which should certainly be questioned with regard to the energy consumption pattern. Therefore it is omitted in the classification according to the WZ 2008 economic sectors.

In `DemandRegio` the information for natural gas in the industry and CTS sector includes information on non-energetic consumption and information on natural gas consumption for industrial electricity and heat production. The following applies to the data for electricity: electricity consumption from industrial self-generation and the conversion sector.

The spatial resolution of industrial and CTS sectors is carried out in a multi-stage process. The electricity and gas consumption is then calculated for each economic "sector10" (WZ) and district based on the number of employees subject to social security contributions as ENaG. Within the stages, data records from the `DemandRegio` database are used.

For these two sectors, the temporally high-resolution modelling is based on standardized load profiles specific to the economic sector and district. With the help of these profiles, the results from the spatial modelling are distributed over the time steps of the year. Here, 15-minute time steps are predominantly selected, with the exception of gas consumption in the CTS sector, where the profiles offer an hourly resolution.

3.2.2 Cross-border flow rate data

In order to perform a simulation that reflects as nearly as possible the true network behaviour, it is necessary to take into account the gas flow that enters and exits the country. Regarding the gas exchanged between Germany and the neighboring countries, two data sources are compared and studied: the one from the German Network Agency (German: Bundesnetzagentur) and the one from the ENTSOG transparency platform.

The Bundesnetzagentur (BNetzA) is the German main authority for network infrastructure, promoting competition in the markets for energy, telecommunications, post and railways to guarantee the efficiency of our country's vital networks. They are a consumer protection authority, that also safeguards the interests of the people using these networks [65]. The data provided is based on calculations by the Federal Network Agency based on data from the transmission system operators [65]. This platform provides daily data starting from January 2022.

ENTSOG stands for European Network of Transmission System Operators for Gas. Its role is to facilitate and enhance cooperation between national gas transmission system operators (TSOs) across Europe, to ensure the development of a pan-European transmission system in line with European Union energy and climate goals. Their transparency platform (ENTSOG-TP) provides regular information on gas supply and demand for the European market and delivers common operational tools to ensure network security and reliability [56]. This platform provides hourly data roughly from 2018 to 2023, however, for some specific border points not all the years are available.

After comparing the data from these two different sources, four main inconsistencies have been found:

1. From BNetzA data, the import from Russia decreased from June 2022 and completely cut from August 2022. While ENTSOG-TP never cuts it down to zero, even if there is a gradual decrease of this import.

2. BNetzA takes into account a net export of natural gas to Switzerland, while ENTSOG-TP has a net import.

3. On analysing the ENTSOG-TP aggregated data for the cross-border gas flow with Belgium, it seemed that not all the network nodes were accounted for, some of them were not considered in the aggregated data.

4. It was found that the flow rate cross-border data with Belgium exceeded the maximum capacity of the pipelines from April to December 2022.

The comparison between the two datasets highlighted some weaknesses in ENTSOG-TP data. Since Bundesnetzagentur is the Federal Network Agency, the data provided by this platform are considered to be more accurate, and therefore have been chosen for this thesis.

As mentioned previously, Bundesnetzagentur provides data about the import and export amount of natural gas of Germany from and to the neighboring countries. However, the data only has a daily resolution, while the domestic demand time series has an hourly resolution. Therefore, to have a unified time step for the simulation, based on the hypothesis that the cross-border flow does not vary significantly during the day, the hourly cross-border flows are generated by simply averaging the daily demand.

Figure 3.15 shows the measured gas flows that have been imported into Germany. It is worth noting that the recorded import quantity also includes possible ring flows. This refers to cross-border gas flows that leave Germany at a border and are redirected back to Germany elsewhere. The representation of the Russian imports in the graph refers exclusively to the gas flows via North Stream 1.

For the purpose of this thesis and taking into account of the current situation. The import from Russia has not been considered, since North Stream 1 is no more in operation since August 2022 and is not set to resume operation in the near future.

Figure 3.16 shows the measured gas flows of the quantities of gas exported from Germany to the adjacent countries. It can be noticed that the exported quantities are much lower than the imported ones, due to the fact that Germany is mostly an importing country. A sizeable export can be noticed towards Czechia.

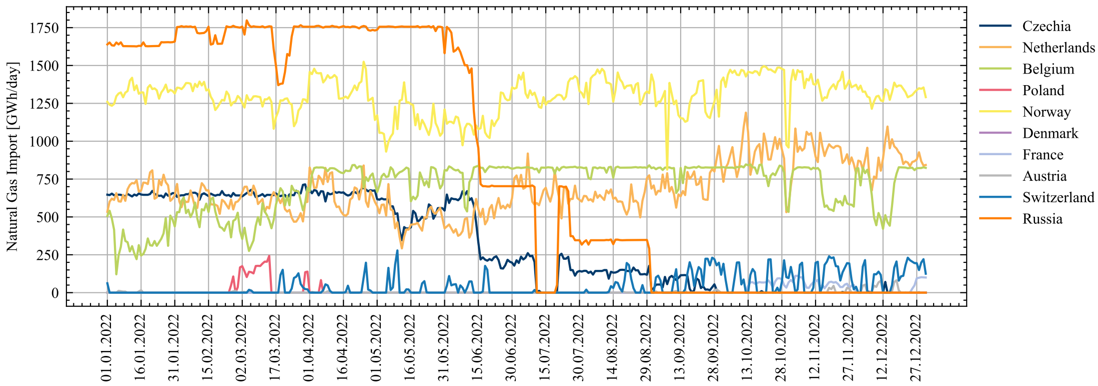

Figure 3.15: BNetzA Import

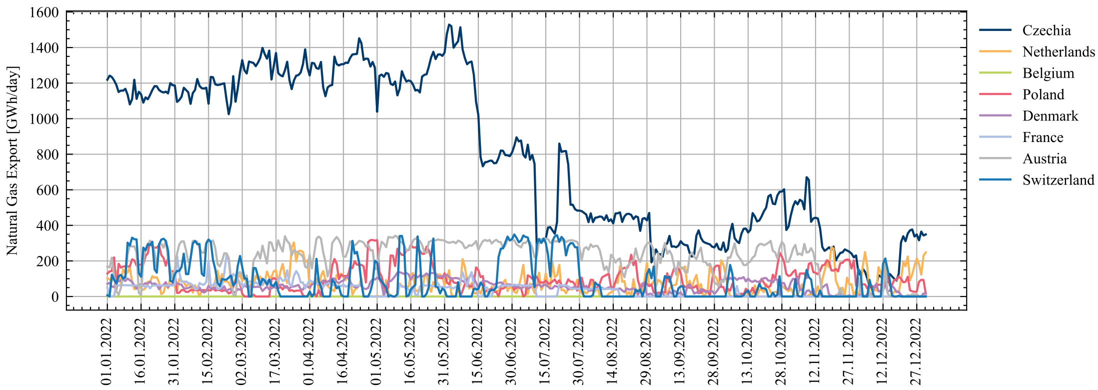

Figure 3.16: BNetzA Export

With the aim of analysing the net cross-border flows between Germany and the neighboring countries, the exports are subtracted from the imports. The net flow towards each country is summarised in the table below, where the negative values indicate a net import from that country during the year and a positive value indicates a net export.

Country	Unit	Value
CZ	m^3/s	518.21
NL	m^3/s	-675.61
BE	m^3/s	-770.15
PL	m^3/s	102.02
NO	m^3/s	-1429.60
DK	m^3/s	63.75
FR	m^3/s	29.34
AT	m^3/s	233.53
CH	m^3/s	49.28

Table 3.2: Net import/export

3.3 Hydrogen Injection Data

The data for hydrogen injection are generated starting from weather data, that enable the calculation of renewable energy production, and `DemandRegio` electricity consumption data, that take into account the consumption of electricity.

The weather data are from the "Open Power System Data" (OPSD) dataset [66], This project aims to create a platform dedicated to freely accessible data for modelling electricity systems. Their efforts involve gathering, verifying, processing, documenting, and furnishing data that are openly accessible but presently challenging to utilize.

The OPSD dataset provides hourly weather data for Europe. In particular, within this data package, it is possible to find radiation and temperature data, the spatial coverage encompasses all the European countries.

Another dataset developed in the same OPSD project contains data about the renewable power plants of some European countries [67]. For Germany, it provides information about individual power plants, all renewable energy plants supported by the German Renewable Energy Law (EEG). The data provided include the renewable energy source, the electrical capacity and the geographical location of the power plants.

For the purpose of this thesis, only solar and wind power plants are taken into account. Thanks to the data described before, electricity production from these power plants is calculated. Then this value is confronted with the electricity demand value provided by `DemandRegio`: from the electricity produced by the renewable plats, the electricity demand is subtracted. The surplus of electricity produced by renewable energy sources is then fed to the gas grid in the form of hydrogen. However, since in the real world the conversion of electricity into hydrogen is performed by electrolyzers, it is important to take into account the conversion efficiency of these devices. Currently, the electrolyzer efficiency for the production of hydrogen is around 50-60%. For this thesis, the value of 52% is chosen [68].

The obtained dataset is an hourly profile of the energy injected as hydrogen into the gas network, for the NUTS-2 regions of Germany. Out of the 38 NUTS-2 regions in Germany, only 28 have at least one hour per year of electricity surplus and, therefore, of hydrogen injection. In figure 3.17 the hydrogen injection (only for some regions) is shown.

According to the calculations, the renewable electricity produced results to be roughly 192.4 TWh, which is in accordance with the data provided by [69] for the same year. On the other end, the curtailment of this electricity (that is used in this thesis as the surplus to be converted into hydrogen), is about 61.9 TWh. Therefore, the curtailment of renewable electricity is about 32.2% of the total electricity produced by renewable energy sources. The total gas consumption in

Germany provided by `DemandRegio` is, in terms of energy, 659.2 TWh. Hence, hydrogen could contribute by providing the 9.4% of this demand.

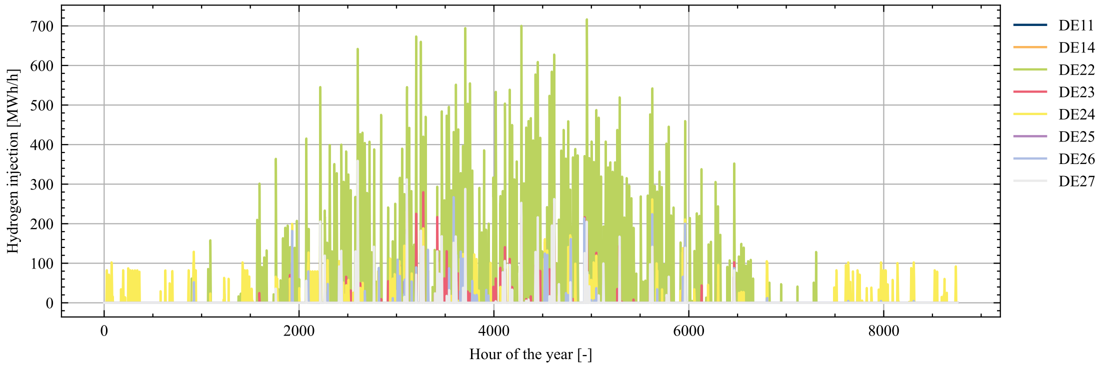

Figure 3.17: Hydrogen injection of some regions

3.4 Final Dataset

In order to obtain a complete dataset to feed the simulation tool, it is important to assign the demand to every node of the network in a coherent way.

1. Domestic demand

   As already said in 3.2.1, the NUTS-3 spatial resolution of `DemandRegio` pairs well with the spatial resolution of the `SciGRID_gas IGGIELGN`, which refers to the same districts. To assign the demand to the `IGGIELGN` nodes, there are three cases:

   - The NUTS-3 district is represented by a unique node in the `IGGIELGN` dataset: in this first case all the demand for the district is assigned to one node.
   - The NUTS-3 district is represented by more nodes in the `IGGIELGN` dataset: in this case the demand is equally divided in all the nodes.
   - The NUTS-3 district is not represented by any node in the `IGGIELGN` dataset: in this third case, the demand for the district is assigned to the nearest NUTS-3 district present in the `IGGIELGN` dataset, by taking into account the distance between the centroids of the districts.

   Regarding the time-varying demand for the year 2015, the temporal resolution is already hourly, therefore no further work is needed.

2. Cross-border demand

   The cross-border demand is assigned to the nodes of the network that are abroad and do not represent a reference node, which is a starting point for the network. The same procedure of domestic demand is adopted: the flow rate is uniformly divided for all the nodes that represent the country in the `IGGIELGN` dataset. Regarding the time-varying profiles, data from 2022 are used. In fact, it is better to use more recent data for cross-border flows in order to take the recent geopolitical situation into account. As already mentioned in 3.2.2, Bundesnetzagentur data have a daily resolution. Hourly data are obtained with the hypothesis that this flow rate does not vary considerably during the day, therefore the daily flow is spread across the 24 hours to obtain an hourly profile.

3. Hydrogen injection

   The surplus of renewable electricity that is then fed to the gas grid as hydrogen has a NUTS-2 spatial resolution, therefore the aggregation of this data has a higher level. In this case, special "hydrogen nodes" are created where the electricity surplus is located. These nodes are then connected to the main network with short pipes. The hydrogen injection data have already an hourly temporal resolution, no further modifications are needed.

A recap of the different demand datasets and their main characteristics is shown in figure 3.18

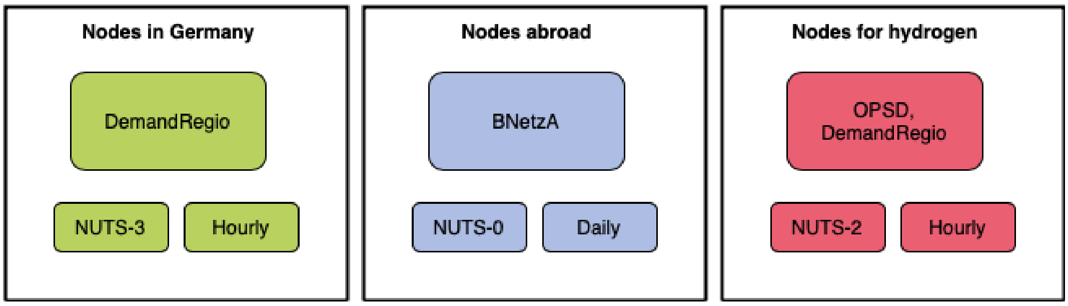

Figure 3.18: Demand datasets

Chapter 4

Case Study Simulation and Discussion

4.1 Scenario With Natural Gas

4.1.1 Steady-state simulation with natural gas

This first case study regards the steady-state simulation of the German gas transmission network. The data from `DemandRegio` 3.2.1 and Bundesnetzagentur 3.2.2 are averaged for the whole year and the simulation is performed. The results are shown and explained in the following pages.

In figure 4.1 it is possible to see the pressure in every node and the flow rate in every pipeline of the network. Here, for a better visualization of the data, the absolute value of the flow rate is displayed.

The pressure of the reference nodes, whose characteristics are described in section 3.1, is set to be 70 bar. Therefore, due to the absence of compressors in this simulation, 70 bar is the highest pressure in this gas network. The largest part of nodes in Germany have pressure between 60 and 70 bar. Germany receives natural gas mainly from Norway (North-West), Netherlands and Belgium (West) but also from some eastern European countries, this is why the pressure is higher in these zones and lower in the central and southern parts of the country. The same consideration can be done for the flow rate. It can be observed a higher flow rate at the left and right boundaries of the network: they represent the import flow from the neighboring countries.

Six nodes with pressure lower than 50 bar are left outside of this visualization but they are displayed in Table 4.1.

These nodes are in the vicinity of very big cities: Berlin and Munich. Therefore, since the demand in these cities is higher, the pressure drops significantly.

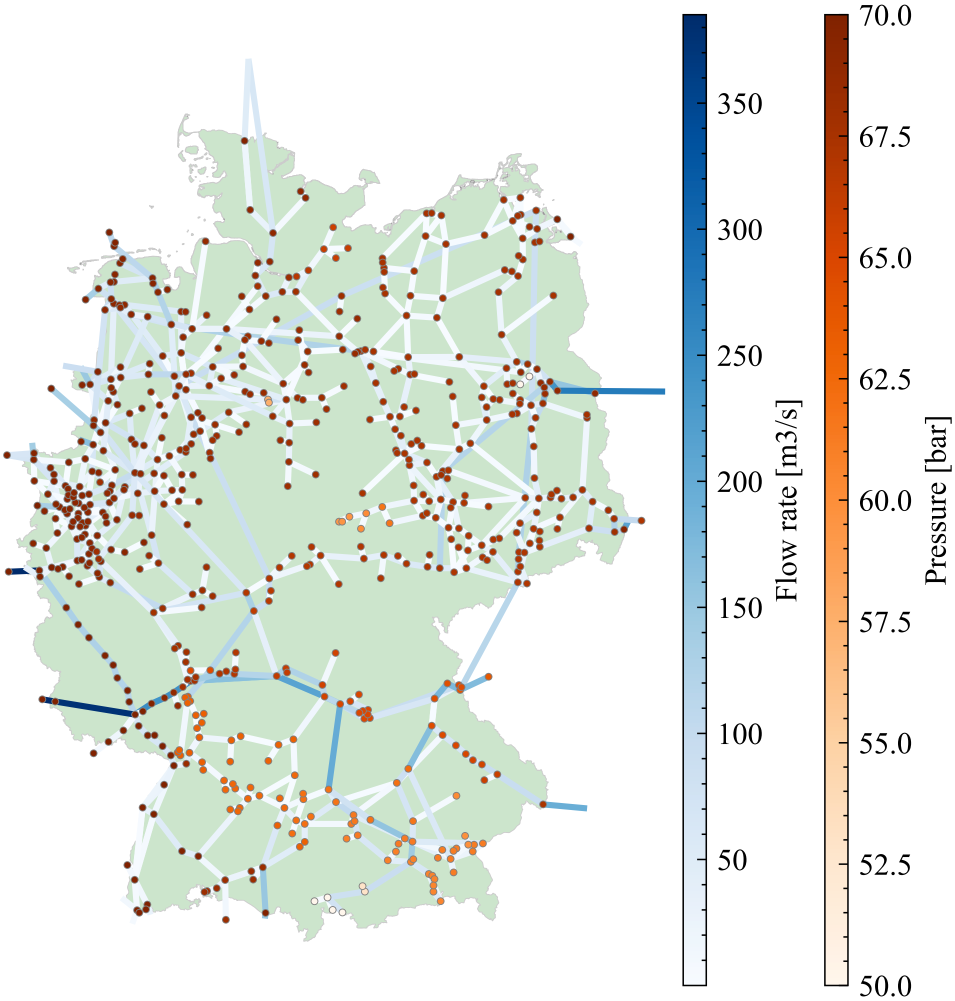

Figure 4.1: Pressure and flow rate in the German gas transmission network

Node index	Pressure [bar]	Location
392	28.98873	Berlin
605	28.98572	Berlin
88	48.36389	Munich Region
89	48.36033	Munich Region
90	48.34452	Munich Region
649	47.98922	Munich Region

Table 4.1: Nodes with pressure lower than 50 bar

As previously mentioned, in Figure 4.1 the absolute value of the flow rate is shown. This is for better visualization, since for some pipelines the flow rate is negative. The negative flow rate indicates that the gas flows in the opposite direction with respect to the flow direction hypothesized by the `SciGRID_gas` group in the `SciGRID_gas IGGIELGN` dataset. In Figure 4.2 the pipelines affected by the reverse flow are shown. In particular, the arrows represent the direction hypothesized in the `SciGRID_gas IGGIELGN` dataset, while after the simulation with `GasNetSim` we find out that the gas is actually flowing in the opposite direction.

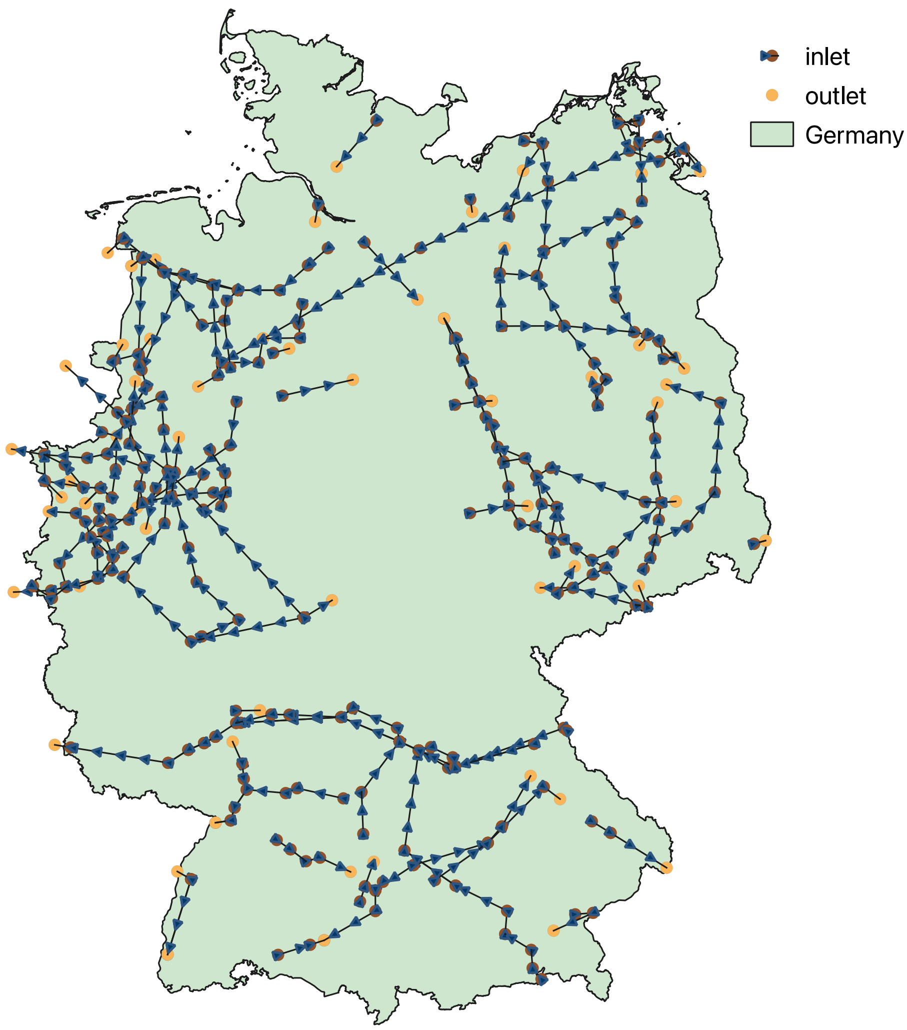

Figure 4.2: Pipelines with reverse flow

There are 333 out of a total of 1019 pipelines identified with a reserved flow direction, so they represent 32.7% of the total. There are several possible reasons for the inconsistency. First of all, the used dataset is highly based on open-source data, which usually does not contain all the details of the network. Besides of this, the pressure values at reference nodes are set to be 70 bar, which is probably not representing the real network operation conditions. Moreover, compressor stations and compressors alongside pipelines are not considered in the simulation. Another reason for the reverse flow could be the absence of storage in the simulation. This snapshot is run with yearly average values that do not take into account the storage facilities that can contribute to pumping the natural gas in the right direction.

The data from `SciGRID_gas IGGIELGN` also provide information about the maximum operating pressure of the pipelines. These pipelines and the information about how much higher is their pressure with respect to the maximum one provided in the data, are shown in Figure 4.3. It can be observed that for some pipelines, the maximum pressure is exceeded. After reviewing the `SciGRID_gas IGGIELGN` dataset, one of the possible reasons is the different network operating pressure of part of the German transmission grid.

The pipelines for which the maximum pressure is exceeded are 312 out of 1019, which represent 30.7% of the total. It can be observed that for the majority of the pipelines, the pressure is exceeded by less than 10 bar. At the same time, for roughly 40 pipelines the pressure is exceeded by more than 40 bar. For these pipelines, the maximum pressure indicated in the dataset is 25 bar or lower. Since the simulation regards the transmission network that usually transports gas at high pressure, it is unlikely that the actual maximum pressure of these pipelines is so low. Therefore, the results indicate that a validation of these values from the `SciGRID_gas IGGIELGN` dataset is possibly needed.

In order to validate the results, the same simulation is run with another gas network simulation tool that uses the SIMPLE algorithm, cited in 2.2.1, instead of the Newton-Raphson method, cited in 2.2.2 for the resolution of the non-linear system of equation.

The relative error between `GasNetSim` and the SIMPLE algorithm is shown in Figure 4.4 and Figure 4.5. The error is calculated as the difference between the simulation results with `GasNetSim` and the SIMPLE algorithm divided by the results from the simulation using `GasNetSim`.

For the majority of the nodes, the error on nodal pressure is very low, between $\pm 1\%$.

For the majority of the pipelines, the error on pipeline flow rate is between $\pm 5\%$.

The issue of reversed flow is analyzed with the tool that uses the SIMPLE algorithm as well. As before, both methods provide very similar results: the number of pipelines affected by reverse flow is in total 333 for both cases, there is one small pipeline affected by reverse flow in `GasNetSim` that is not reversed in the SIMPLE algorithm tool and vice versa.

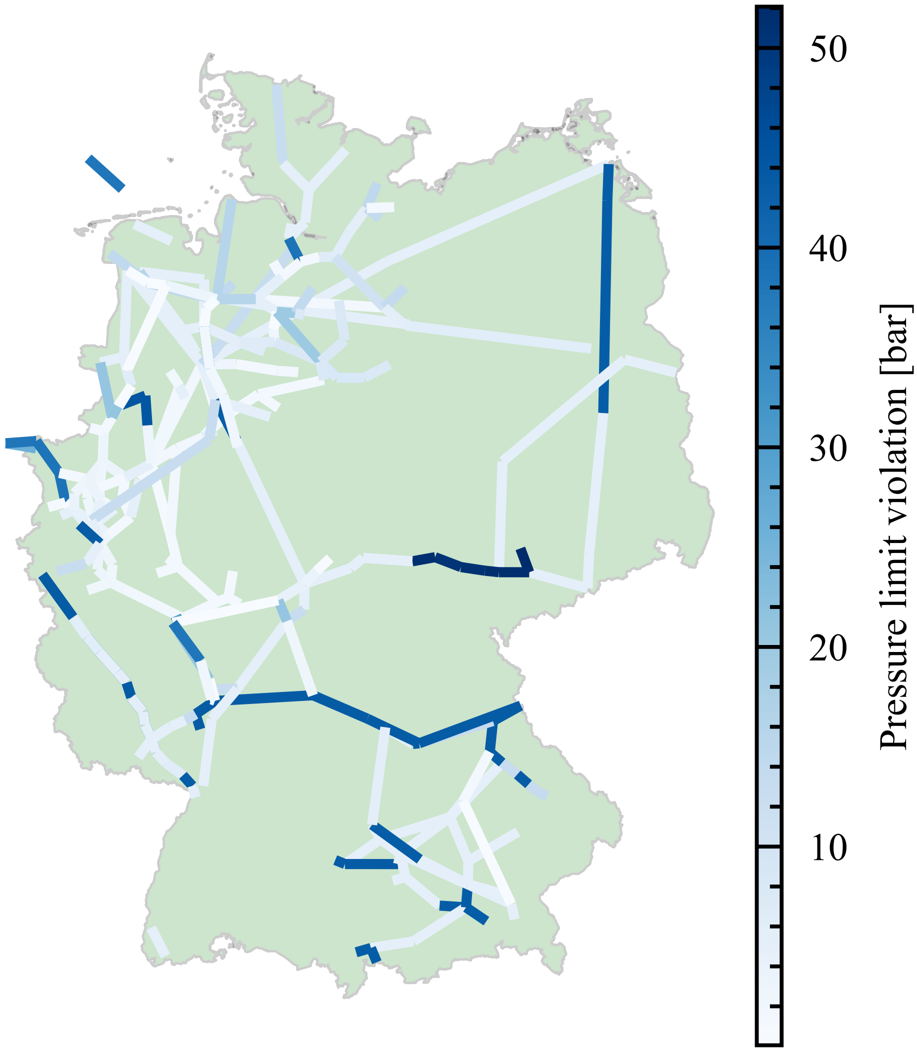

Figure 4.3: Pressure limit violation

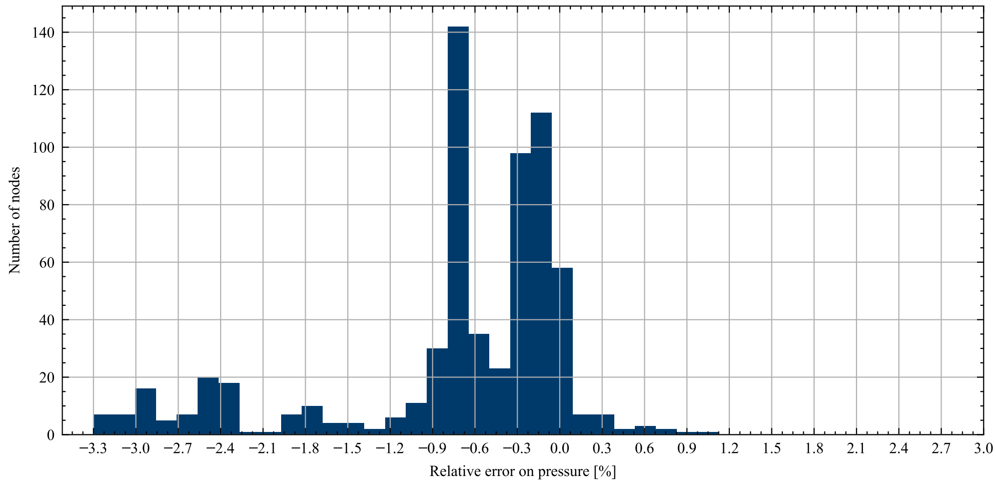

Figure 4.4: Relative error for the nodal pressure

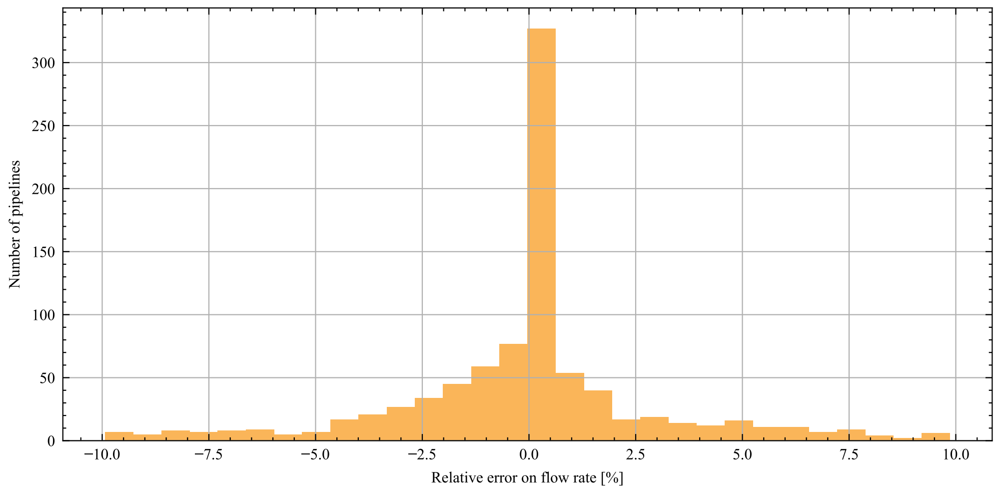

Figure 4.5: Relative error for the pipeline flow rate

In order to understand why the two tools do not provide perfectly overlapping results, it is important to highlight the differences between them:

1. Compressibility factor

   As mentioned in 2.1.2, there are two main methods to calculate the compressibility factor: correlation or equation of state. In particular, `GasNetSim` utilizes the GERG-2008 equation of state 2.1.2, while the SIMPLE algorithm tool utilizes the Papay formula 2.1.2.

2. Gas mixture

   The gas mixture that the two tools use is slightly different. On one hand, `GasNetSim` uses a mixture that mainly includes methane and ethane but also other hydrocarbons in lower quantity, such as propane, butane, etc. On the other hand, the SIMPLE algorithm tool considers a gas mixture composition of 100% methane.

3. Parallel pipelines

   By parallel pipelines we mean those pipelines that have both the inlet and outlet node in common. In fact, for vast transmission networks, is very common to have more pipelines running in parallel between the same locations, in order to transport all the needed natural gas. The issue of parallel pipelines is treated in different ways in the two tools: in `GasNetSim`, and in particular, in the Jacobian matrix used in the Newton-Raphson solver, the derivative of the flow rate is calculated singularly for every parallel pipeline and successively all the derivatives are summed up in the Jacobian matrix. In the SIMPLE algorithm, however, the parallel pipelines are always taken into account separately.

4.1.2 Time series simulation with natural gas

In order to deeply study the behaviour of this gas network under different conditions, an hourly time series simulation is run for the day of maximum demand of natural gas. In this way, it is possible to analyse the network under the most stressed operating conditions. The results are summarized in the figures below.

In Figure 4.8 the network at the most stressed hour of the day, 8 o'clock in the morning, is shown. As expected, the flow rates are higher with respect to the steady-state case shown in Figure 4.1.1. The nodal pressures are generally lower, especially in the southern part of the country.

Since the pipeline flow rate is higher, it is worth to check the loading percentage with respect to the maximum capacity indicated in the dataset. The result is shown in Figure 4.7.

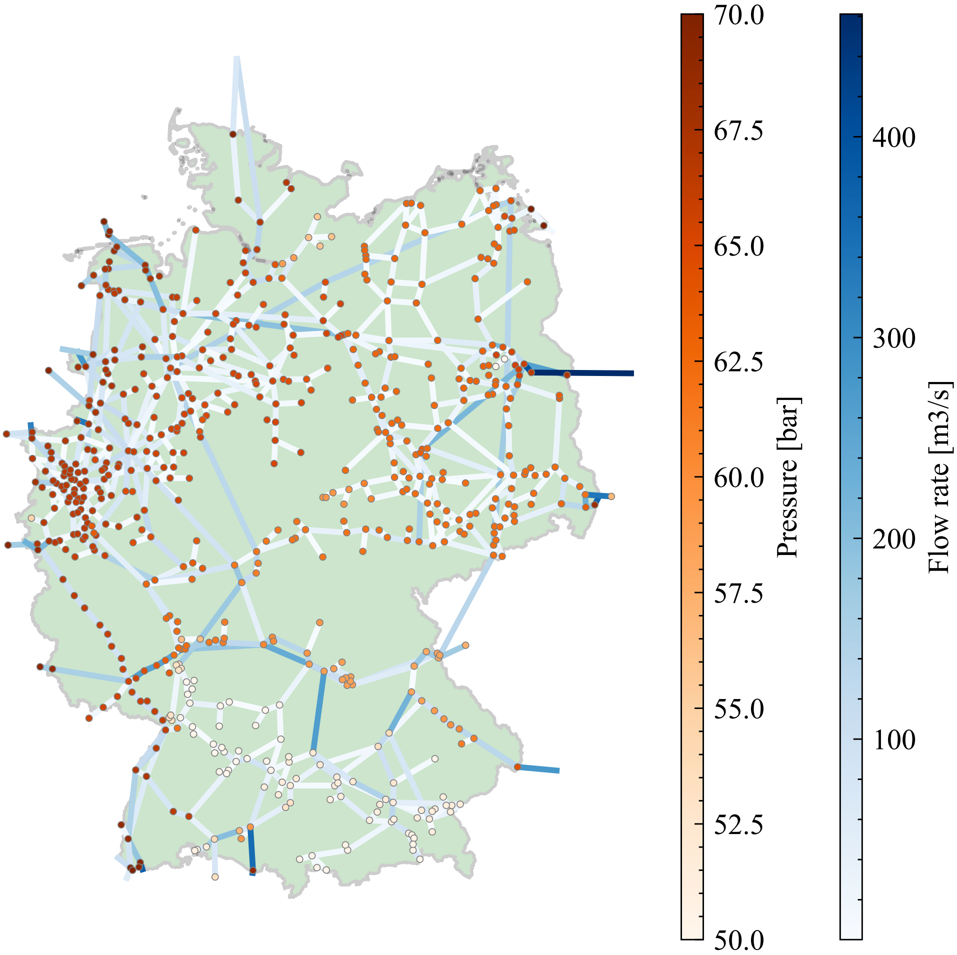

Figure 4.6: Pressure and flow rate at 8 am

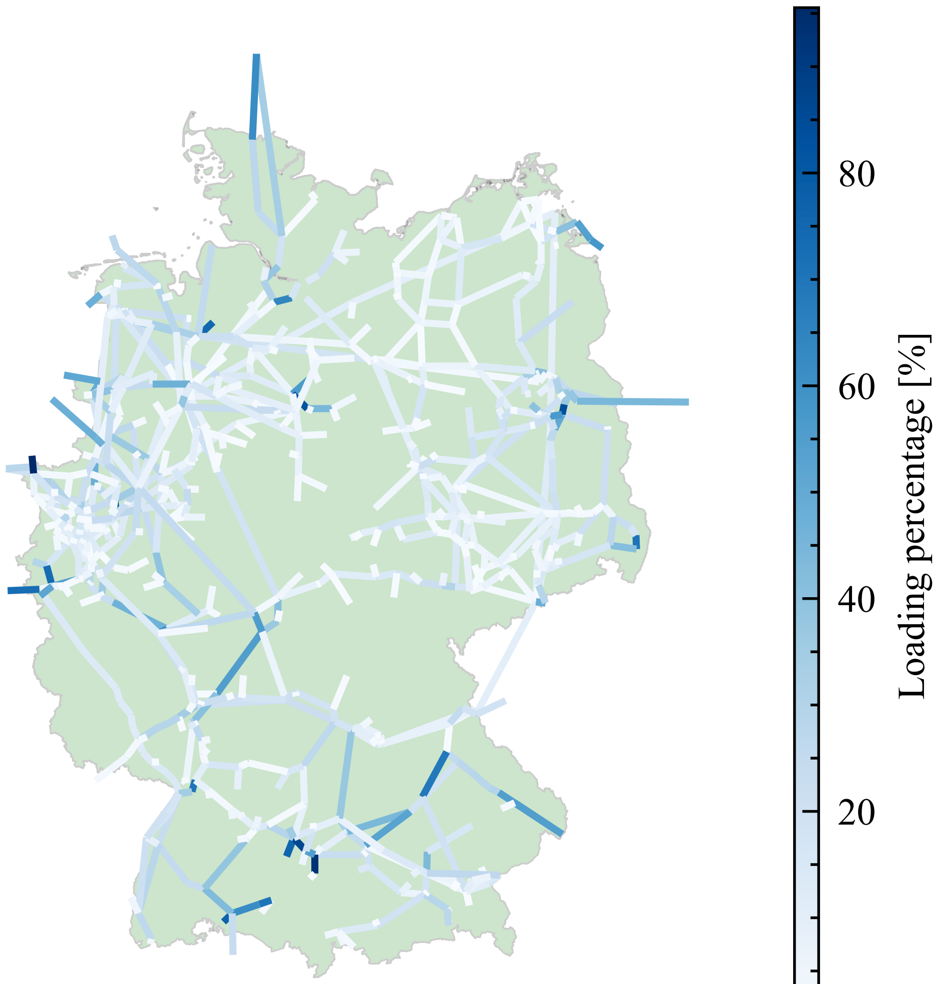

Figure 4.7: Loading percentage of gas pipelines

It can be observed that the majority of the pipelines transport gas with a loading percentage between 40% and 50%. However, many pipelines, especially very short pipes near to the import points, experience a loading percentage that is higher than 80%. Moreover, there are fewer than 30 pipelines, representing the 2.8% of the total, experience a loading percentage higher than 100%. As before, these overloaded pipelines are located at the boundary between Germany and the neighbouring countries and are very short. Furthermore, some of these are parallel pipelines.

In Figure 4.8 the pressure and flow rate during the day for the most stressed pipeline are plotted.

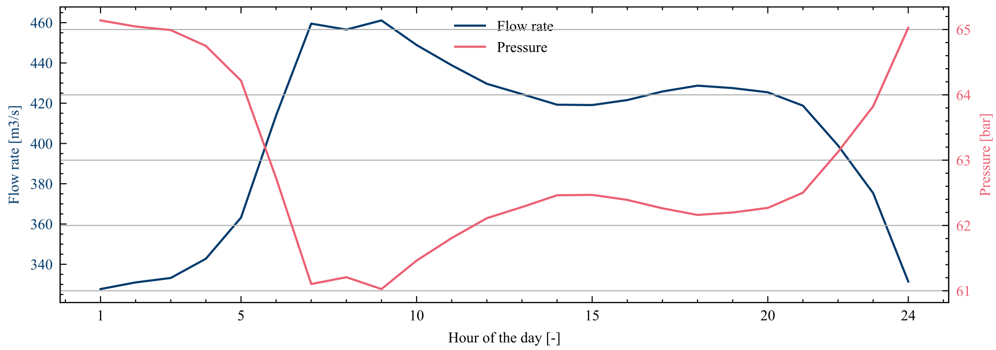

Figure 4.8: Pressure and flow rate in the most stressed point of the network

The maximum demand, as expected, occurs in the morning, between 8 and 10 a.m. During the afternoon the demand is almost constant, while during the evening, between 6 and 9 pm, it rises again. The lowest demand occurs during the night, between 11 pm and 6 am.

In Figure 4.9 the import flow rate, namely the flow rate injected in the grid from the reference nodes, is shown.

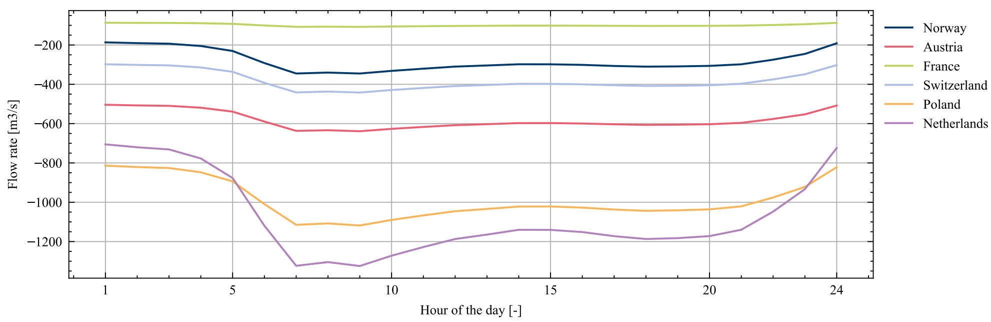

Figure 4.9: Import flow rate

The flow rate is plotted with respect to the country from which it is provided and it is almost constant during the day.

4.2 Scenario With Hydrogen Injection

After the natural gas network simulation, we move further on to the network simulation considering hydrogen-blending into the German gas transmission grid.

The amount of hydrogen injected is derived from renewable generation surplus, as explained in 3.3. According to the current regulations in Germany, the hydrogen injection limit in the gas network is 10%, one of the highest in Europe [34]. The authorities of the country report the existence or the planning of projects aiming to increase hydrogen acceptance limits in their gas transmission network [34]. For this reason in this thesis, a 20% hydrogen blending in natural gas is considered.

Two different hourly simulations with hydrogen blending are run: the summer day with the highest hydrogen injection and the winter day with the highest hydrogen injection. The results are shown in the section below.

4.2.1 Time series simulation for a summer day with hydrogen blending

In this section, the hourly results from the time series simulation with a 20% hydrogen blending of the summer day with the highest hydrogen injection are shown.

In Figure 4.10, the hydrogen percentage in the nodes of the network at 9 a.m. is displayed. This particular time of the day is chosen because it is the hour with the highest hydrogen injection. Therefore a better estimation of the consequences that hydrogen blending has on the network operation can be derived.

It is possible to notice the highest concentration of hydrogen in the north-western part of the country. This results from the fact that this region has a high wind generation potential, as well as the installed wind energy generation capacity. At the same time, the electricity demand is not very high in this region, which means that the renewable power generation is usually higher than the demand.

Figure 4.11 shows the hydrogen percentage at the nodes of the network at 4 a.m.

Comparing this figure with the previous one, it is possible to see in the northwest of the country the hydrogen percentage is almost the same, while in the northeast and southeast, the hydrogen percentage is much lower during the night. This difference can be explained by the fact that the hydrogen injected in the north-west mainly comes from wind farms. At the same time, in the eastern part, there is also some hydrogen coming from the surplus of photovoltaic plants, which do not produce energy during the night.

In order to study the impact of hydrogen injection on pressure and flow rate, the nodes with a hydrogen concentration above 5% and the pipelines to which they are connected are plotted and displayed in Figure 4.12. The same pipelines and

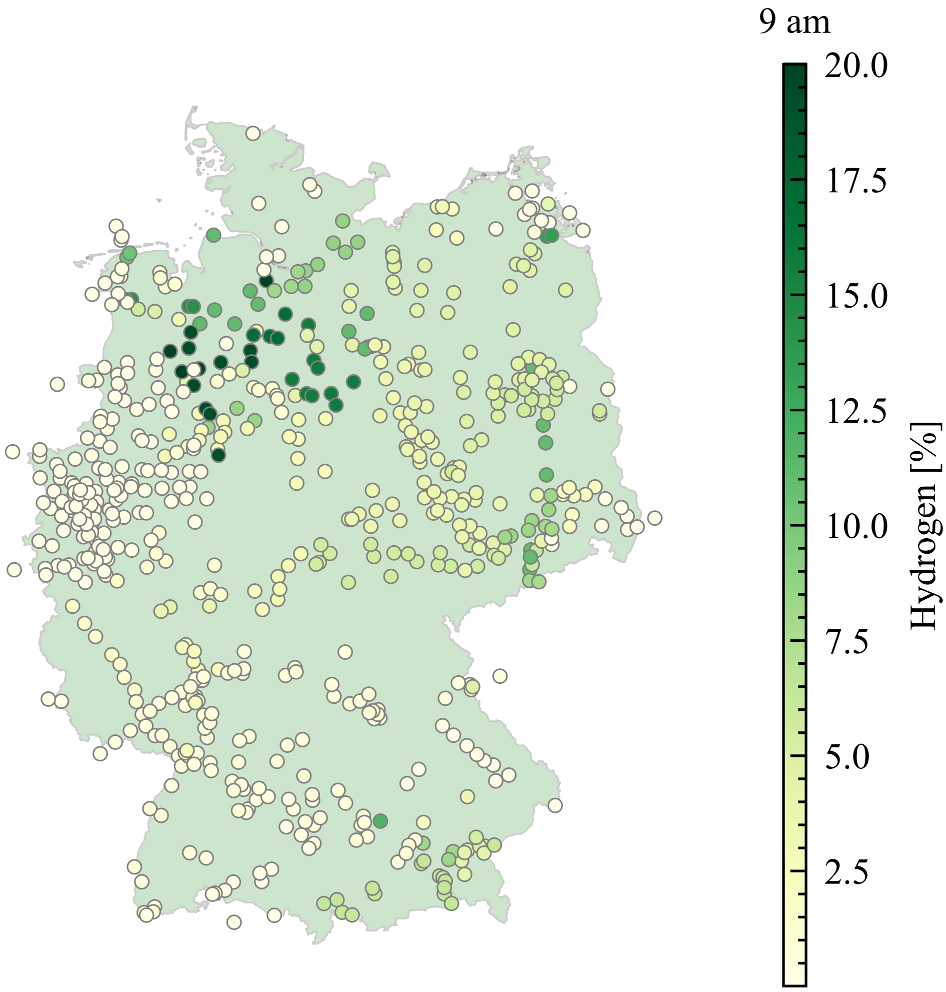

Figure 4.10: Hydrogen percentage in the nodes at 9 am

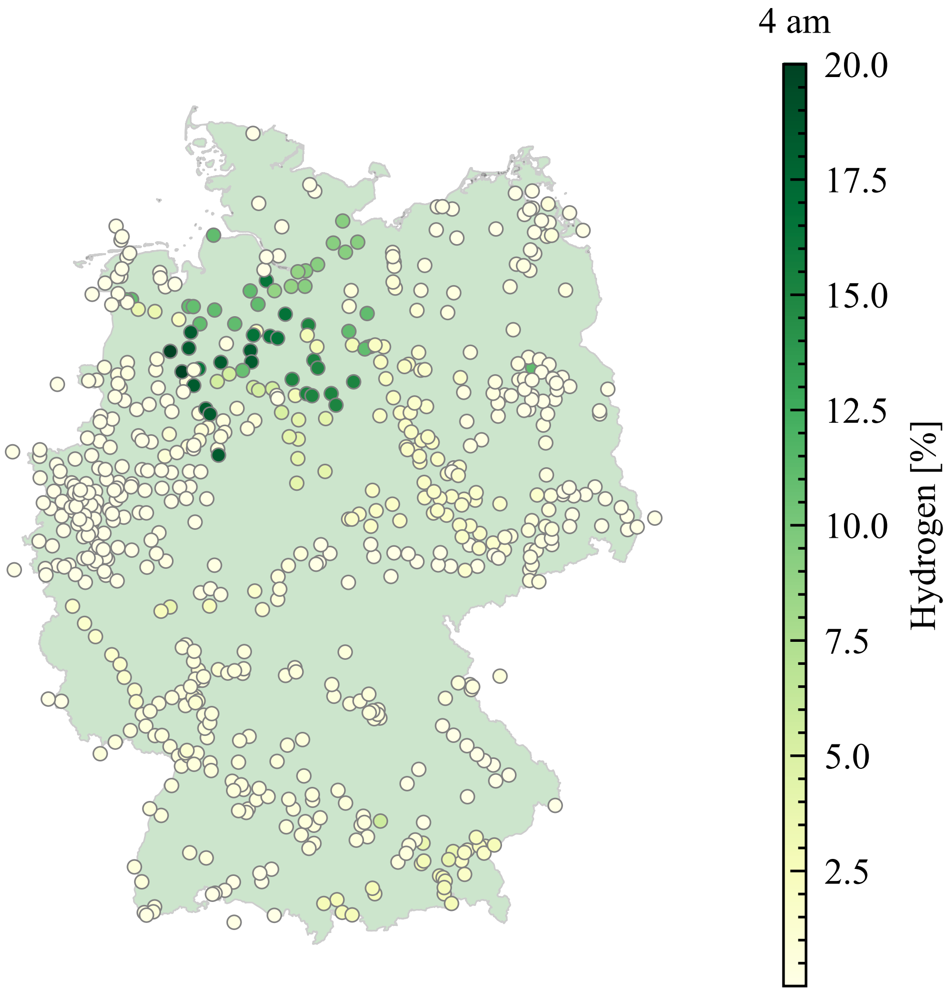

Figure 4.11: Hydrogen percentage in the nodes at 4 am

nodes, but for the case in which only natural gas is flowing in the network are displayed in Figure 4.13, in order to compare the two cases.

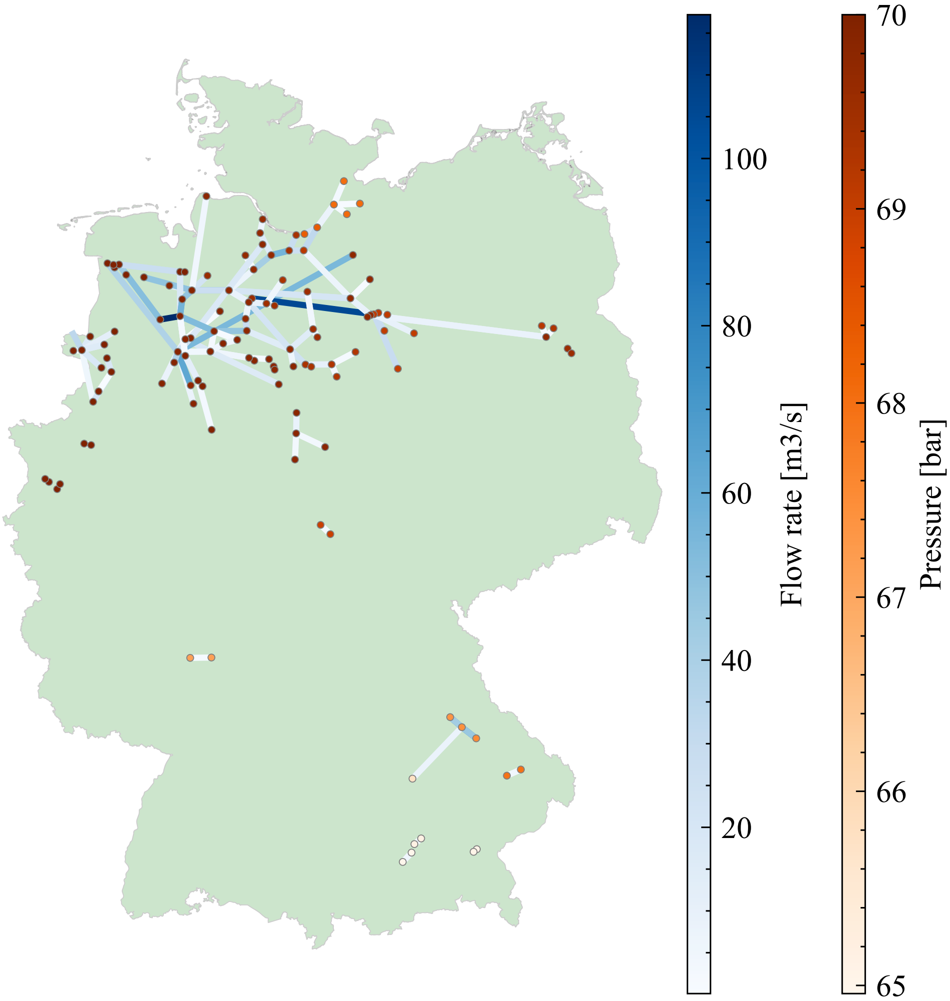

Figure 4.12: Pipelines and nodes with the highest hydrogen concentration

Some pipelines and nodes are not connected to the main cluster in the northwest part of the country, this is because the isolated nodes are located near renewable power plants with an electricity surplus, therefore hydrogen is directly injected into those nodes.

As expected, in order to satisfy the energy demand, since the hydrogen heating value is smaller than the one of natural gas, a higher gas flow rate is needed. Especially in zones with very high demand, the higher flow rate could generate too much stress on the walls of the pipelines. The nodal pressure in the case of hydrogen blending is, in general, lower than in the case of natural gas only. This

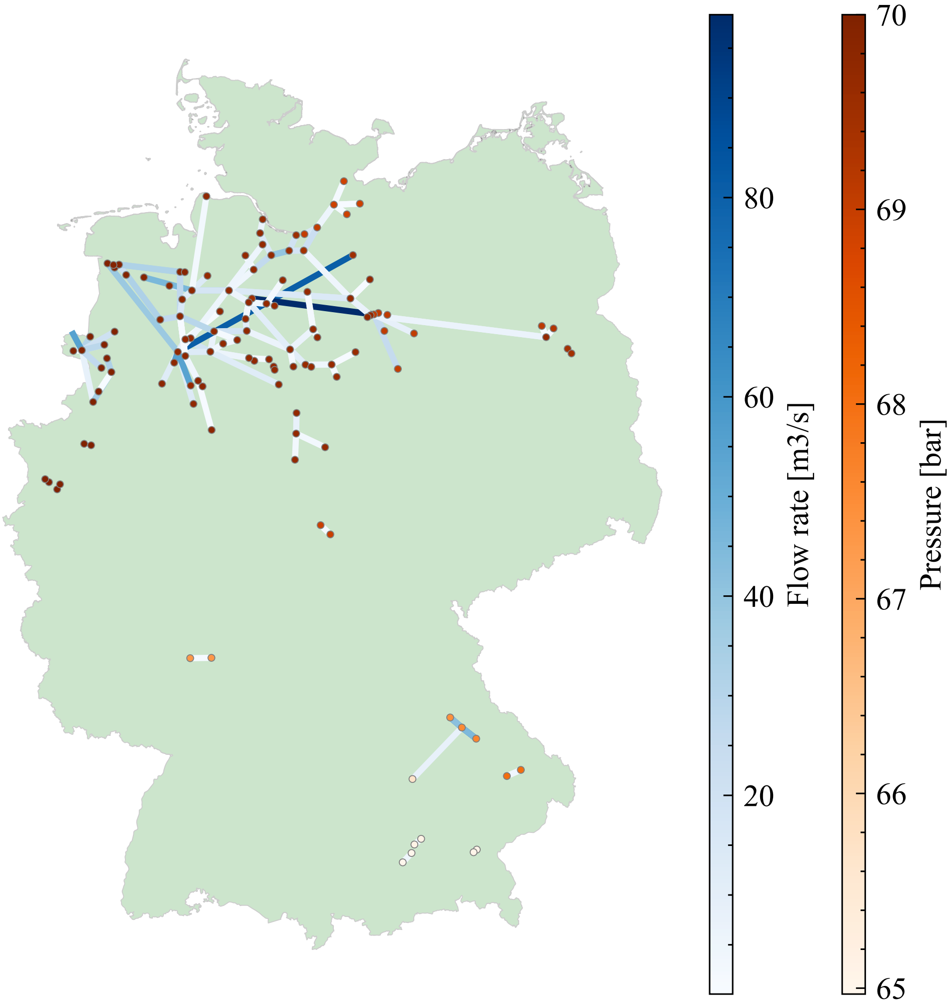

Figure 4.13: Pipelines and nodes for the case without hydrogen blending

can be noticed in the upper-central part of the plot.

In the figure 4.14 the hourly pressure in the node with the highest hydrogen concentration is shown for the cases with and without hydrogen blending. The pressure does not vary a lot during the day because this node is just after a reference node, so there is not much pressure loss. However, it can be seen that in the case of hydrogen blending, the pressure is lower. This is also justified by the physical characteristics of hydrogen, in particular, the lower density of the hydrogen molecule with respect to natural gas leads to a lower pressure.

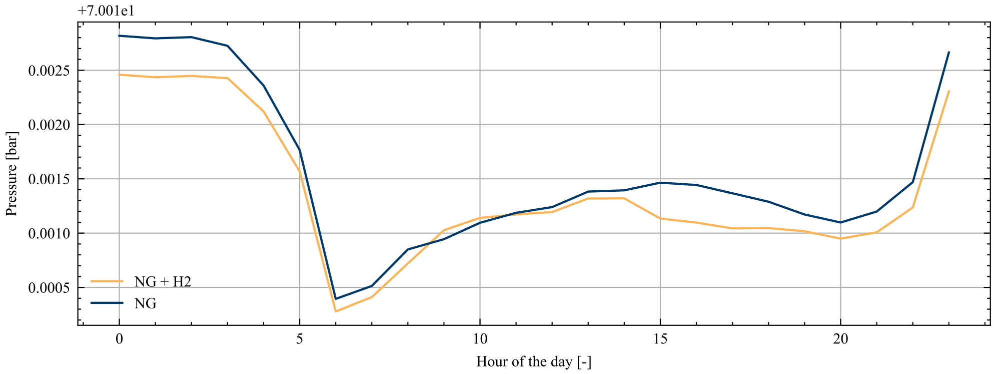

Figure 4.14: Pressure at the node with the highest hydrogen concentration

In the figure 4.15 the hourly flow rate in the pipeline for which the node with the highest hydrogen concentration is the outlet node is shown for the cases with and without hydrogen blending.

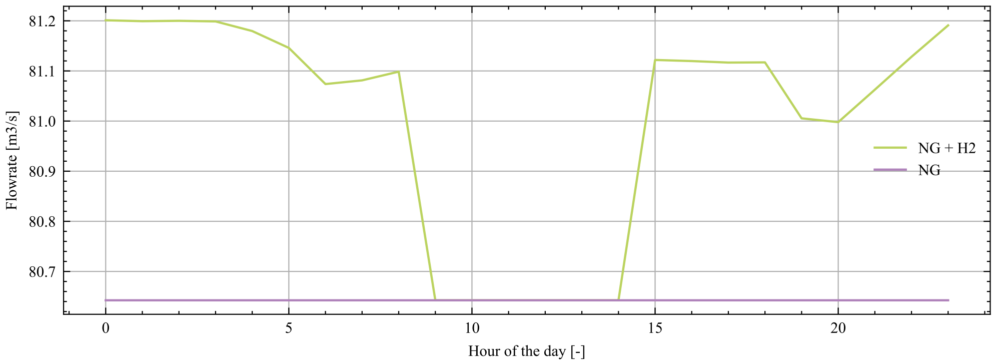

Figure 4.15: Flow rate at the pipeline with the highest hydrogen concentration

Just as in figures 4.12 and 4.13, there is an higher flow rate in the hydrogen blending case, in order to provide the user with the requested amount of energy. It can also be noticed that from 9 am to 2 pm there is no hydrogen in this pipeline, this can signify that there is no renewable surplus at these hours of the day.

4.2.2 Time series simulation for a winter day with hydrogen blending

In this section, the hourly results from the time series simulation with a 20% hydrogen blending of the winter day with the highest hydrogen injection are shown.

Figures 4.16 and 4.17 display the hydrogen concentration in the nodes of the network at 9 am (the hour with the highest injection) and at 4 am.

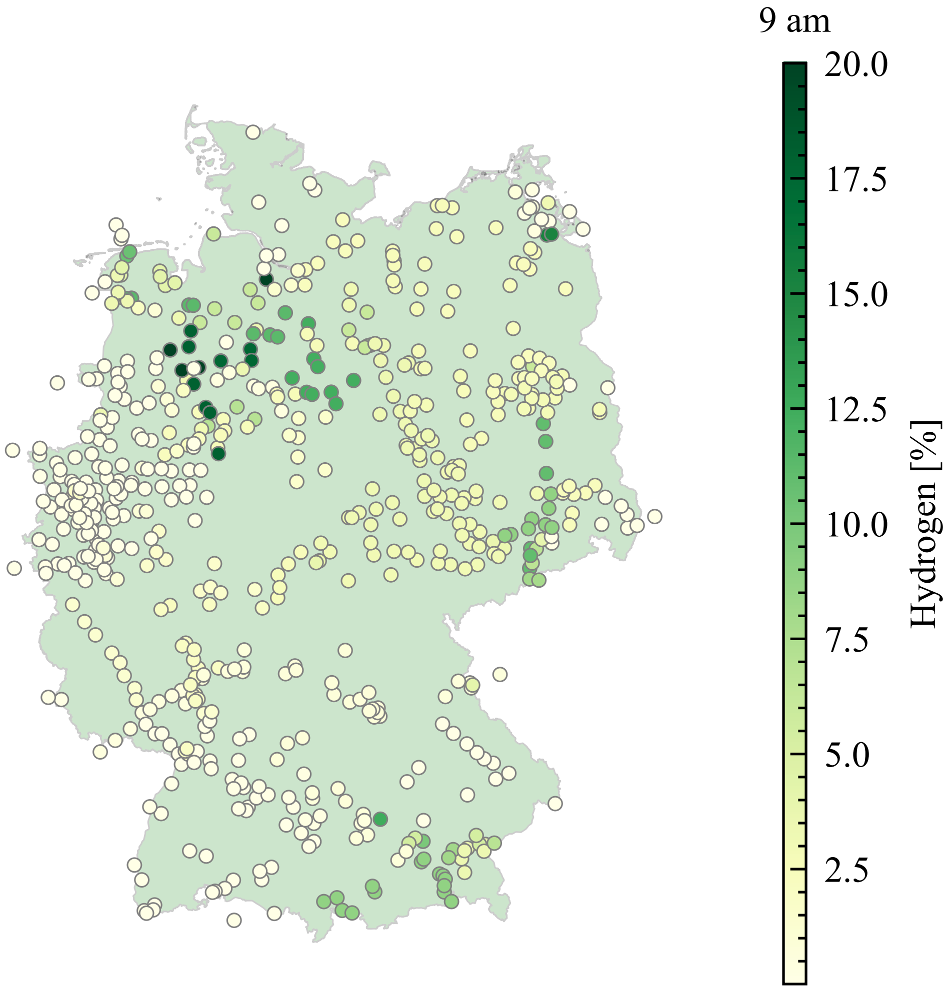

Figure 4.16: Hydrogen percentage in the nodes at 9 am

In contrast to the summer case shown in Figure 4.2.1, there is no appreciable difference between the hydrogen concentration in the morning and during the night in winter. This can be explained by the difference in hydrogen injection between day and night is mainly due to the photovoltaic plants that produce more electricity

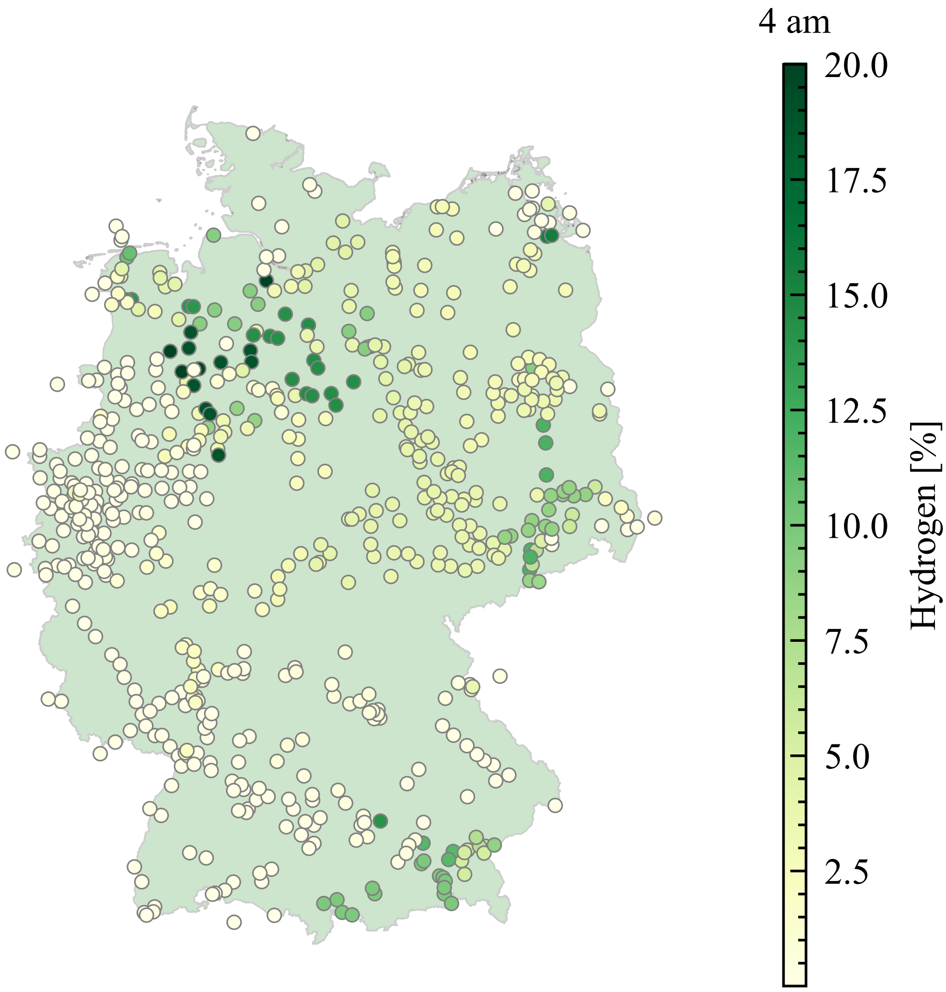

Figure 4.17: Hydrogen percentage in the nodes at 4 am

during the day. However in winter, PV plants produce less energy and there is no surplus coming from their electricity, therefore there is no hydrogen injection from this kind of plant.

In figure 4.18 the nodes with a hydrogen concentration above 5% and the pipelines to which they are connected are shown. For comparison, the same nodes and pipelines for the case with natural gas only are shown in figure 4.19.

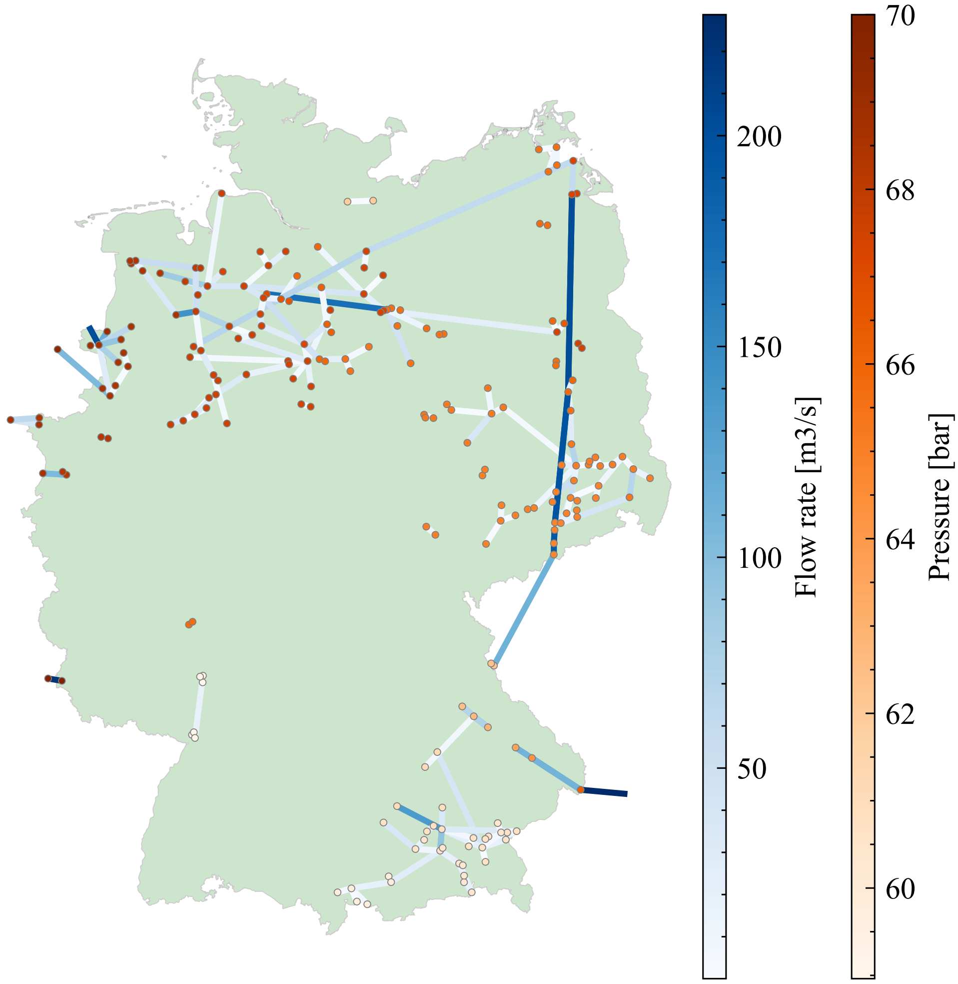

Figure 4.18: Pipelines and nodes with the highest hydrogen concentration

Since in winter PV plants generally produce less electricity while the electricity demand is higher, the surplus from renewable sources and consequently the hydrogen injection, is very low. Therefore it is possible to say that in winter the hydrogen injection does not impact the flow rate and the pressure in the network as much as in summer.

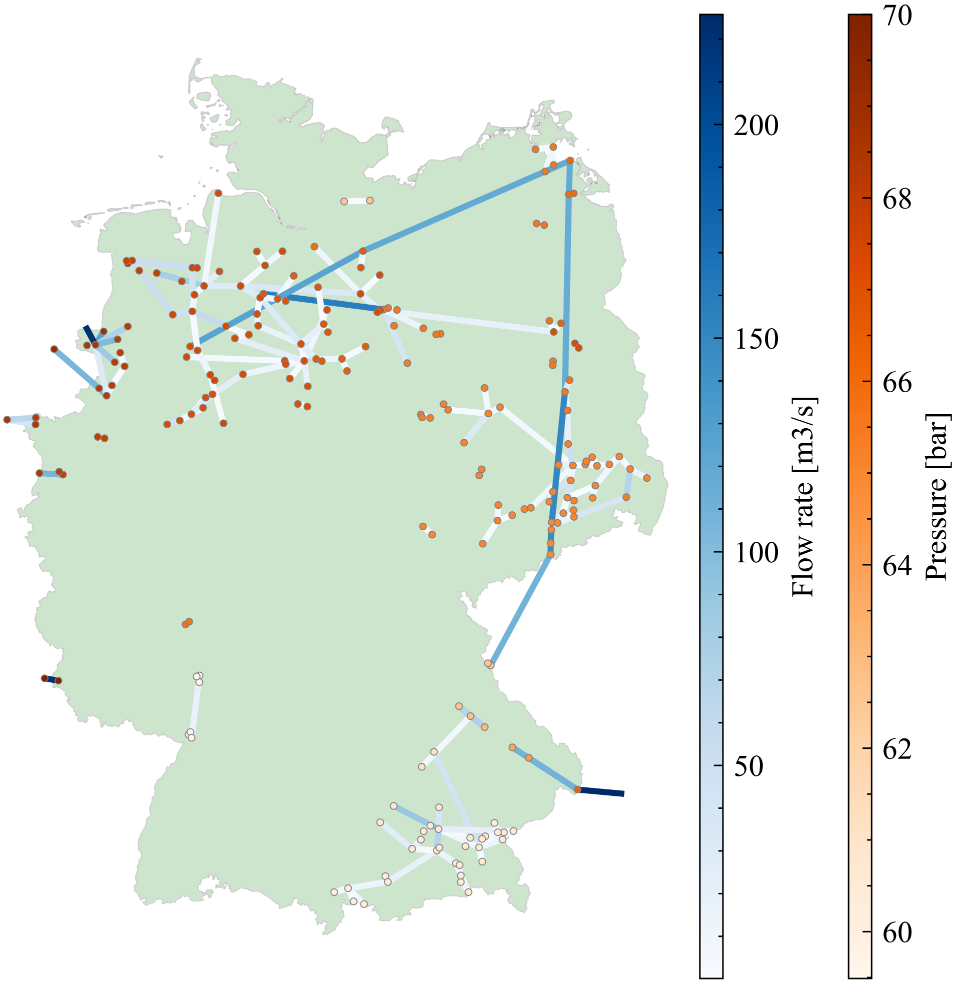

Figure 4.19: Pipelines and nodes for the case without hydrogen blending

Figure 4.20 and Figure4.21 show the pressure at the nodes with the highest hydrogen injection and the flow rate in the pipeline for which this node is the outlet node.

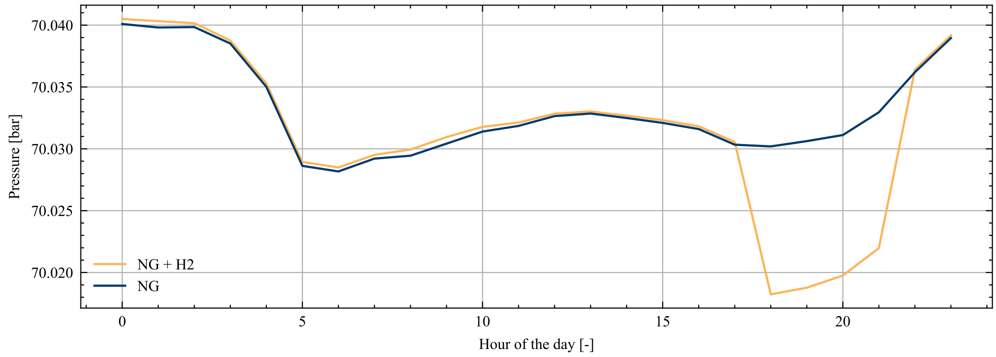

Figure 4.20: Pressure at the node with the highest hydrogen concentration

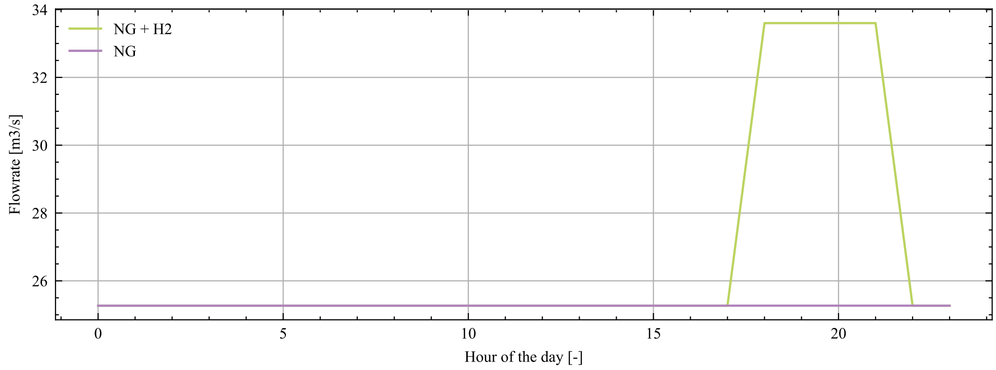

Figure 4.21: Flow rate at the pipeline with the highest hydrogen concentration

It is obvious that hydrogen injection is only present between 6 and 9 pm. In these hours of the day, as already observed in Section 4.2.1, the pressure is lower and the flow rate is higher.

Chapter 5

Conclusions and Outlook

This work aims to evaluate the feasibility of creating a German gas transmission grid model using only open-source datasets and tools. Based on this model, simulation-based analyses of the German gas transmission network are performed, with a special focus on green hydrogen blending in natural gas.

To achieve these goals, the steady-state mathematical model and the thermal model of gas pipelines are analysed. In addition, an overview of the different simulation methods is provided, including a focus on the chosen simulation tool, `GasNetSim`. Then, all the used datasets and the data processing work are explained in detail. Lastly, the simulation was performed and the results are shown.

In particular, the equations of the steady-state flow and thermal equations of the gas pipelines and their derivation are presented. The related variables, such as the calculation of friction factor and compressibility factor are highlighted and different methods to calculate them, as well as some considerations about these methods, were provided. Then, the mathematical formulation of the Newton-Raphson method is provided, which is a well-known approach for solving a system of non-linear equations. Lastly, a section is dedicated to `GasNetSim`, the chosen simulation tool. In this section, the functionalities of the tool are listed and its modelling and simulation approaches are explained.

Afterwards, the used datasets are introduced. To run the simulation, demand data are needed. The used datasets were analysed one by one and the work to adapt them to the simulation purpose of this thesis was pointed out. Regarding the domestic demand for natural gas, the datasets `SciGRID_gas CONS` and `DemandRegio` were compared. Even if `SciGRID_gas CONS` provides European data, `DemandRegio` provides hourly data, takes into account public holidays for each Bundesland and also non-energetic gas demand, for this reason it was chosen. Also for the cross-border flow rate data two different sources were compared: data available from Bundesnetzagentur and ENTSOG-TP. The data from Bundesnetzagentur is considered to be more accurate and more in accordance with other sources, therefore it is chosen over ENTSO-TP data. Although the data from Bundesnetzagentur are daily and not hourly, with the hypothesis that this flow rate does not vary considerably during the day, the daily flow is spread across the 24 hours to obtain an hourly profile. Regarding hydrogen injection data, they are derived from the electricity generation surplus of renewable energy sources, to study the green hydrogen injection effect on the network. Renewable electricity generation is calculated from open-source meteorological data and renewable power plant data. From the comparison with electricity demand data, the surplus of renewable electricity is obtained, which is assumed to be used to produce green hydrogen and to be blended into the natural gas network.

The last piece of the puzzle to perform the needed simulations is the topology data. The data about the network nodes and pipelines are obtained from the `SciGRID_gas IGGIELGN` dataset. The data processing work consists of isolating the German gas network from the larger European one provided by the dataset, finding the reference nodes, namely the starting points of the network, removing unrealistic data that could lead to wrong results and subnetworks isolated from the main transmission network.

The result obtained from the steady-state simulation run with natural gas showed consistent results in line with expectations. The nodal pressure and pipeline flow rate are higher near import points and lower in the central part of the country due to pressure losses. However, two main problems are highlighted. First, the maximum pressure limit of part of the network provided by the dataset may be too low for a transmission network. Therefore, it is suggested that these limit values should be double-checked and verified with other sources. Second, many pipelines are identified with reverse flows. The reverse flow rate is mainly due to the absence of data about the compressor location and its operation. For validation, the same simulation is run with another simulation tool developed in MATLAB that uses the SIMPLE algorithm instead of the Newton-Raphson method. Overall, the two tools provided rather similar results, with the error on the nodal pressure between $\pm 1\%$ for nodal pressure and $\pm 5\%$ for pipeline flow rate. The differences between the two tools are mainly caused by the different modelling approaches and assumptions for some variables, such as the compressibility factor calculation, the gas mixture composition, and so on.

Afterwards, an hourly time series simulation of the day of maximum natural gas demand is performed. It aims to identify the points in which the network can be more vulnerable and subjected to stress. As expected, the flow rates are higher compared with the steady-state simulation performed before, which is based on the yearly average demand. It can be also noticed that some pipelines are overloaded concerning the maximum capacity provided by the data. Most of the pipelines are very short pipelines near the import points. This can be explained by the fact that they usually experience very high flow rates.

Moving on to the hydrogen injection part, four time-series simulations are performed to highlight the impact of the green hydrogen on the network parameters: the hourly simulations of the day with the highest hydrogen blending in the network in winter and in summer, and the hourly simulations of the same two days without hydrogen blending. From the results of the summer day simulation that displays hydrogen distribution in the network nodes in the morning and the night, it can be seen the effect of photovoltaic plants in comparison to wind farms. In fact, in the night the hydrogen concentration in the network is lower because there is no photovoltaic electricity generation and therefore no energy surplus from this resource. Moreover, it can be seen that in the pipelines with the highest hydrogen percentages, the flow rate was higher with respect compared with the case without hydrogen. This is because hydrogen has a lower energy content than natural gas, therefore a higher volumetric flow rate is needed to provide the same amount of energy. From the hourly trend of pressure and flow rate in the node and pipeline with the highest hydrogen concentration, it is observed that the pressure is lower and the flow rate is higher with respect to the case without hydrogen. Here, particular attention is needed because pressure always has to be higher than a certain limit that depends on the kind of pipeline (transmission or distribution network) and the flow rate can not exceed the maximum capacity of the pipeline.

Regarding the winter simulation, it is seen that there is no significant variation between the hydrogen concentration in the network in the morning versus during the night. A possible reason is the absence of PV generation during the day, leaving wind farms as the only green hydrogen source. Despite the analysed day being the one with the highest hydrogen injection in winter, the injected quantity is still very low and is not possible to assess the impact of this blending in the network. Possible reasons for this are the lower renewable energy production and the higher electricity demand in winter.

Overall, it is possible to conclude that the existing open-source datasets and tools provide enough information for steady-state and time-series simulation of the German gas transmission network. However, the data quality of the datasets still has a large room for improvement. Further work should be performed on improving the data quality of the gas network datasets. A possible solution is to establish cooperation with TSOs to obtain more detailed information about the network and how the network is operated. In addition, real measurements are also needed for the validation of the network simulation. Moreover, to achieve a more accurate representation of the real network operation, analyses based on dynamic simulations should be considered.

Nomenclature

ϵ	Internal pipeline roughness
μ_{JT}	Joule-Thomson coefficient
ρ	Gas density
ρ_r	Reduced density
θ	Pipeline slope angle
A	Pipeline cross-section area
C_{pipe}	Pipeline coefficient
c_p	Specific heat at constant pressure
D	Pipeline diameter
d	Pipeline relative density
EOS	Equation of state
f	Friction factor
g	Gravitational acceleration
h	Gas specific enthalpy
L	Pipeline length
M	Molar mass
M_{air}	Air molar mass
p	Gas pressure
p_{avg}	Average gas pressure

p_i	Inlet gas pressure
p_j	Outlet gas pressure
P_{pr}	Pseudo-reduced pressure
p_{st}	Standard pressure
Q	Gas volumetric flow rate
R	Specific gas constant
Re	Reynolds number
T	Gas temperature
t	Reciprocal of the pseudo-reduced temperature
T_{avg}	Average gas temperature
T_i	Inlet gas temperature
T_j	Outlet gas temperature
T_{pr}	Pseudo-reduced temperature
T_{st}	Standard temperature
T_s	Soil temperature
U_L	Linear overall heat transfer coefficient
v	Gas velocity
Y	Reduced density
Z	Compressibility factor
Z_{avg}	Average compressibility factor

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