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Analysis of hydrogen integration into the gas grid of Hamburg by means of gas quality tracking

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Analysis of hydrogen integration into the gas grid of Hamburg by means of gas quality tracking

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Abstract

The injection of hydrogen into natural gas distribution networks poses challenges for gas grid operators regarding the correct billing of end customers and safety. In this thesis, two particular aspects of hydrogen integration shall be examined on the gas grid of Hamburg. The first aspect is compliance with the billing rule according to the DVGW technical code G685 when a large amount of hydrogen is admixed. Different measures, focusing on the division of the downstream grids into more suitable calorific value districts, shall be evaluated to address this aspect. The second aspect is compliance with a certain blending limit of hydrogen which is assumed to be 20 % by volume. A methodology shall be developed to ensure this compliance when there is a risk that the limit may be exceeded. To investigate these tasks, various scenarios in which hydrogen is injected at different locations in the grid are examined using gas quality tracking.

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Abbreviations

CV	Calorific Value
DVGW	Deutscher Verein des Gas- und Wasserfaches e.V
HD	Hochdruck (High-pressure)
MD	Mitteldruck (Medium-pressure)
ND	Niederdruck (Low-pressure)
NKP	Netzkopplungspunkt (Network interconnection point)
SLP	Standard-Lastprofile (Standard Load Profiles)
RLM	Registrierende Leistungs-Messung (Recording Power Measurement)

Mathematical operators

$\sum$	Summation
$\widehat{(\cdot)}$	Corrected

Symbols

H	Calorific Value
V	Volume

Subscripts

corr	correction
eff	billing
en	entry
h	hourly
i	individual exit node
m	monthly
n	standard condition
net	network
s	superior

1 Introduction

1.1 Motivation

In recent years, there have been many studies and discussions about integrating renewable gases such as biomethane or hydrogen (H_2) into the already existing natural gas infrastructure to gradually decrease the reliance on natural gas. Green hydrogen in particular receives a lot of attention since it can be produced through the electrolysis of water using surplus electricity and then directly injected into gas pipelines, which helps to alleviate the storage and transportation problems. This concept is known as "Power to Gas" or P2G. Apart from this, gas grids in urban areas have large capacities and are capable of transporting energy over long distances with very low losses [1]. Nevertheless, there are some limitations of injecting hydrogen with regard to safety issues and correct billing of end customers. The calorific value of hydrogen is lower than that of natural gas by a factor of three, making it challenging for gas grid operators to determine an accurate billing calorific value in accordance with DVGW Worksheet G 685-2. From the technical perspective, hydrogen's blending limit depends on the gas infrastructure's tolerance and sensitivity, which varies from network to network, and therefore requires a case-by-case assessment [2]. These issues can be addressed by means of gas quality tracking.

Gas quality tracking tools are becoming more widely accepted to determine the billing calorific values of a gas grid as well as analyze the feasibility of injecting gases with different qualities such as hydrogen. To comply with the technical rules regarding billing and to ensure certain limits of hydrogen concentration will not be exceeded for safety reasons, two proposals, i.e., the division of the downstream grid and the shutdown of hydrogen injection after a certain time respectively, are studied using SmartSim.

1.2 Scope of the thesis

This thesis focuses on two aspects regarding the blending of hydrogen into the existing gas grid of Hamburg. The first aspect aims at compliance with DVGW Code of Practice G 685-2 by sorting suitable downstream feed-in points into multiple calorific value districts (CV districts) under the assumption that the CV districts may be hydraulically separated by the gas grid operator of Hamburg. The second aspect targets compliance with an assumed H_2-blending limit of 20 % by finding suitable criteria for stopping the

hydrogen injection when there is a risk that the limit may be exceeded. Then, with the results of how long the hydrogen can be injected based on the criteria, arbitrary locations on the grid can be considered suitable or not for the hydrogen injection.

1.3 Structure of the thesis

This thesis consists of six parts. After the introduction, the fundamentals of gas quality tracking based on SmartSim and compliance with the technical rules are explained in chapter two. The details of the city gas grid of Hamburg are then described in chapter three. In chapter four, the first aspect regarding the division of the Hamburg's downstream grid is addressed to ensure correct billing. This includes the procedure of examining the high-pressure and downstream networks and the subsequent results of different H_2 scenarios. In addition, statistics on the number of new calorific value districts and their corresponding regulators are provided. The second aspect regarding the shutdown of hydrogen for safety reasons is evaluated in chapter five. This chapter shows the results of the criteria for an appropriate shutdown as well as the comparison of the H_2 feed-in quantities of four locations in the grid of Hamburg, ensuring a certain limit of hydrogen is not exceeded. Recommendations on how the study can be further developed in addition to the summary of the thesis are presented in the final chapter.

2 Fundamentals of gas quality tracking method

In this chapter, a brief overview of the SmartSim software is provided and the compliance with the technical regulation regarding gas billing in Germany and H_2 concentration is summarized.

2.1 The SmartSim software

Gas quality tracking is a digital procedure for determining the billing calorific values in a gas supply area with several points of injection. The gas being supplied can be natural gas of different origins as well as renewable gases such as biomethane and hydrogen even though their respective qualities may vary greatly. According to DVGW worksheet G 685-2, gas quality tracking is considered one of the substitute methods to determine the billing calorific value when the measurement or reconstruction of calorific value is not economically reasonable [3]. The use of gas quality tracking is mainly for local and regional distribution networks where the metering infrastructure at the exit nodes is usually poorly developed.

The SmartSim software carries out a simulation process based on a set of input data to identify the gross calorific values and further gas properties for all exit nodes of distribution gas networks. In this part, details on the necessary inputs and a brief summary of the calculation kernel in SmartSim are described.

2.1.1 Input

To track gas quality with SmartSim, a number of input parameters are required. They are the topology of the considered network, the gas properties and the pressure at the entry points, the gas volumes at all entry and exit points, the valve positions as well as the pressure at the controllers within the network.

The topology of a network consists of pipes, nodes, pressure regulators, and valves. Information on pipe length, pipe diameter, and pipe roughness is required for every pipe. Regarding the nodes of a network, they can be categorized into three types: entry nodes representing the network inlets, exit nodes representing the network outlets, and none nodes representing the connection points between the pipes, the valves, and the controllers.

The rest of the required data should be available as hourly values so that the flow state through the whole grid can be simulated with a temporal resolution of one hour. At entry nodes of the network, various gas properties, i.e., calorific values, standard density, CO_2 content, and H_2 content can be measured by gas quality devices in compliance with calibration law such as process gas chromatographs (PGC) providing hourly mean values or reconstruction system (REKO) from the upstream network providing daily mean values.

Entry gas volumes are also fundamental and are measured on an hourly basis as well. At the exit points of distribution networks, measured gas volume data are usually not available because of a lack of gas meters there. Therefore, apart from the large customers whose consumed gas volumes are measured (RLM customers), the small end customers' consumed gas volumes are estimated alternatively through standard load profiles [4]. The method using standard load profiles determines the gas exit volumes also as hourly values based on the load profile types, the total customer value [kWh] of each profile type, the daily average temperature, and the associated coefficients of the profile types [5].

Additionally, measured network pressures at representative points and the entries are used to reinforce the determination of the gas volume flow.

2.1.2 The SmartSim method

In general, the computational kernel in SmartSim carries out three steps based on the input data to simulate the flow state and determine the gas properties in the gas network. The calculation is done in a monthly cycle. They are as follows:

- Volume correction
- Hydraulic simulation
- Calorific value tracking ("back propagation")

The output volumes determined by the standard load profile itself are not accurate enough for the calorific value tracking. Hence, a new correction algorithm was developed and applied in conjunction with the use of standard load profiles to improve the accuracy of the exit volumes [6]. The algorithm considers the volume balance of the entire network that relates to the entry volume, the offtake volume as well as the linepack. The offtake volume is the sum of the measured volumes for RLM customers and the unmeasured volumes for SLP customers of all exit nodes. Linepack (ΔV_{net}) refers to the amount of

natural gas stored in the piping distribution system. The volume correction is then calculated from these quantities on an hourly basis [6]:

$$V_{corr} = V_{en} - V_{RLM} - V_{SLP} - \Delta V_{net} \quad (2.1)$$

The determination of the SLP volumes corresponds to a higher uncertainty than the measured volumes at entries and exits, and the linepack. For this reason, the SLP volumes which account for the primary deviation in the volume balance are corrected more strongly. The correction volume in Eq. (2.1) is split among the individual exit nodes (index i) proportionally to the amount of consumption via the following equation [7]:

$$\hat{V}_{corr,i} = \left(1 - \frac{V_{corr}}{V_{SLP}}\right) . V_{SLP,i} \quad (2.2)$$

The total volume of an exit node i is then calculated again as the sum of its downstream RLM volume and its corrected SLP volume [6]:

$$V_{exit,i} = V_{RLM,i} + \hat{V}_{corr,i} \quad (2.3)$$

Only after the exit volumes have been corrected for every hour is the flow in the network simulated to determine the flow state. The information on the flow velocities, masses, and volumetric flow rate in every pipe is then known.

In the final step, using a special gas package model known as the "back-propagation algorithm", the exit volumes are traced back to the entry points so that the fractions of the calibrated entry volumes together with the origins and the transit time are assigned to each exit node.

As a result, the gas quality values for all exit points of the grid can be calculated in hourly resolution via a linear mixing rule. Most importantly, the calorific values at the exit points of a calorific value district can then be used to determine the billing calorific value as a volume-weighted monthly mean in accordance with DVGW worksheet G685.

2.2 Compliance with the technical rules

In this study, two technical rules of DVGW Standards and Codes of Practice need to be adhered to. They are respectively the DVGW G 685-2 regarding gas billing and calorific value, and the DVGW G 260 regarding gas quality specifications when hydrogen is injected into gas networks. The compliance with these rules shall be summarized in the following sections.

2.2.1 Determination of the monthly billing calorific values

Based on the mean value method of the DVGW G 685-2 worksheet, SmartSim calculates the billing calorific values using the calorific values at the exit points. The calorific value districts (CV districts) are created for this purpose and the exit nodes of a district will be billed with the same billing calorific value. From the perspective of a CV district, the feed-in calorific values correspond to the calorific values of the relevant exit nodes simulated by SmartSim. Firstly, since the calculation is performed in a monthly cycle, the monthly gross calorific value for each feed-in point of a district $H_{s,m}$ is calculated as follows:

$$H_{s,m} = \frac{\sum_j^L H_{s,h}(j).V_{n,h}(j)}{\sum_j^L V_{n,h}(j)} \quad (2.4)$$

$H_{s,h}(j)$: superior calorific value at a feed-in point of a district on an hourly basis

$V_{n,h}(j)$: volume in standard state at a feed-in point of a district on an hourly basis

L: number of hours of the calculated month

j: running index from hour 1 to hour L

The monthly gross calorific value $H_{s,m}$ is also the billing calorific value $H_{s,m,eff}$ in the case of a single-sided supply.

$$H_{s,m,eff} = H_{s,m} \quad (2.5)$$

If a CV district has multiple feed-in points, the billing calorific value $H_{s,m,eff}$ results from the volume-weighted averaging of the monthly gross calorific values over all the feed-in points of the district.

$$H_{s,m,eff} = \frac{\sum_i^N H_{s,m}(i).V_{n,m}(i)}{\sum_i^N V_{n,m}(i)} \quad (2.6)$$

$H_{s,m,eff}$: billing calorific value on a monthly basis

$H_{s,m}(i)$: superior calorific value at a feed-in point of a district on a monthly basis

$V_{n,m}(i)$: volume in standard state at a feed-in point of a district on a monthly basis

N: number of feed-in points in the concerned district

i: running index from feed-in point 1 to feed-in point N

Other properties of gas such as the standard density, CO_2 concentration, and H_2 concentration are also calculated as monthly volume-weighted mean by applying the above formulas.

According to the DVGW G 685-2 worksheet, the use of the mean value method described above is only allowable if all the monthly feed-in calorific values of a CV district (equation 2.4) do not deviate by more than 2 % from the billing calorific value (equation 2.6) of that district. This criterion is also known as the so-called "2 % limit" rule and applies to multi-sided districts. The inequality is as follows:

$$-0.02 \leq \frac{H_{s,m}(i)}{H_{s,m,eff}} - 1 \leq +0.02 \qquad (2.7)$$

2.2.2 Integration of hydrogen in natural gas networks

According to the DVGW G 260 worksheet, a uniform limit value for the admixture of hydrogen into the gas infrastructure can currently not be defined yet [8]. Today, it is recommended to blend at most 2 % hydrogen by volume in the distribution networks when compressed natural gas (CNG)-refueling stations are connected to the networks since this is the limitation of gas-fueled cars. Another study has shown that a hydrogen admixture of up to 10 % by volume is permissible in some parts of the natural gas system [9]. The maximum hydrogen concentration of 10 % is only possible if no gas filling stations, no gas turbines, and no gas engines with a hydrogen specification of less than 10 % are connected [9]. Furthermore, it should be ensured that the Wobbe index and methane number of the mixture are not close to the existing limit values for the network. In the future, a blending limit of 20 vol.-% is technically feasible; however, further investigations on material sensitivities, e.g., reduced lifetime, are required [2]. In this study, the hydrogen concentration in the grid shall be examined on the assumption that an admixture of hydrogen of up to 20 % is allowable.

3 Description of the city gas grid of Hamburg

The natural gas network in the city of Hamburg is operated by the operator Gasnetz Hamburg GmbH. The gas network is characterized by a high degree of meshing and complexity. The pipeline system is categorized into three levels of pressure, i.e., high, medium, and low pressure. The grid's infrastructure comprises approximately 1,050 kilometers of high-pressure pipelines, 250 kilometers of medium-pressure pipelines, 6,600 kilometers of low-pressure pipelines as well as around 600 gas-pressure regulating systems, and 160,000 house connections. With this system, gas is supplied to 230,000 customers in the city area. [10]

In the following sections, the network is described respectively from the high-pressure viewpoint and the low-, and medium-pressure viewpoint.

3.1 High-pressure network (HD network)

SmartSim simulates only the HD regional distribution network of the gas grid Hamburg, which is operated at a pressure between 4 and 25 bar [11]. The period under investigation is carried out from February to December 2020. In terms of gas quality, process gas chromatographs (PGCs) are used at the entry nodes for measurement with high accuracy while the metering infrastructure for the outflow is partially developed.

From the perspective of this HD network, natural gas is received from the upstream transmission networks (i.e., GasCade and Gasunie) and is then injected into downstream local distribution networks (i.e., low- and medium-pressure grid of Hamburg). Figure 3.1 illustrates the topology of the regional network of Hamburg with its entry nodes. The HD network is connected to the upstream grid via six network interconnection points (NKP) at three locations. It can be seen that natural gas is fed via one interconnection point at Ohe Twiete in the northern part of the grid, one at Tötensen and one at Leversen in the southern part of the grid, and three at Reitbrook on the grid's south-eastern part. Besides, there are two sewage treatment plants (BGEA) Köhlbrandhöft in the port of Hamburg providing biogas into the center of the regional distribution network [11].

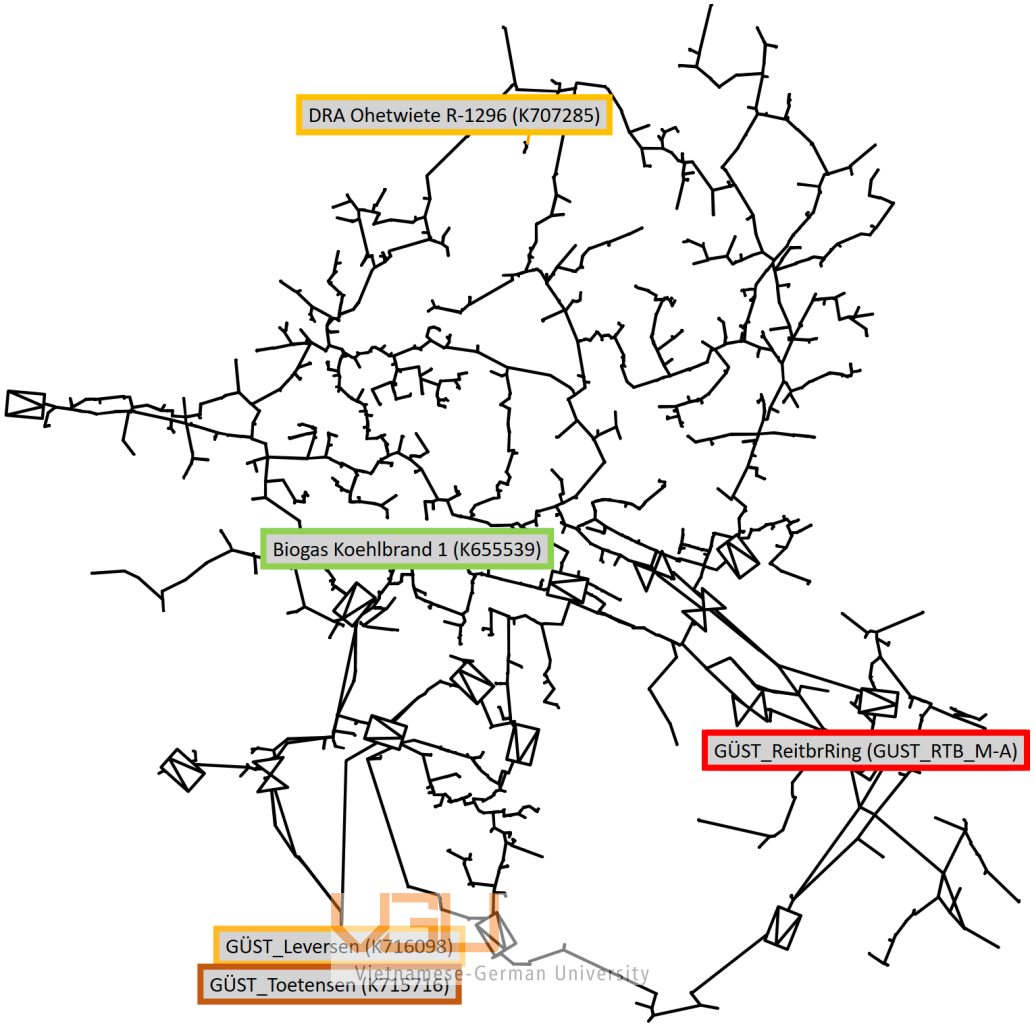


Figure 3.1 The high-pressure network of gas grid Hamburg in SmartSim.

The topology of the HD network includes 611 exit nodes, 244 of which feed gas into the downstream network. The pressure regulating stations at the exit points lower the pressure of gas before supplying it to the downstream network or directly to some large customers. These large customers or industrial customers are characterized as recording power measurements (RLM) customers whose consumed volume is measured.

3.2 Low- and medium-pressure network (ND and MD network)

The medium-pressure grid of the Hamburg network operates at a pressure of 500 mbar while the low-pressure grid operates at a pressure of 60 mbar with a high degree of meshing [12]. Gas meters are often not available here and the consumed gas is estimated via the standard load profile method.

The downstream maps including the pipeline systems with different gas pressures were provided via the Stanet software. Figure 3.2 shows the overview of the medium-pressure grid which is depicted by blue lines. It is characterized by separate lines or sections. The medium-pressure sections can be supplied via one controller or multiple controllers. The former case corresponds to a single-sided district. The latter case corresponds to a multi-sided district (Chapter 4.1), and it is defined with a name and a boundary. The low-pressure grid is shown in Figure 3.3 and is depicted by green lines. Unlike the MD grid, it is characterized by a high level of meshing, especially in the northern area. The HD network (black lines) and the name of the pressure regulating systems are embedded in every map. Additionally, the defined CV districts' borders are marked with red color.

The map of the ND system with boundaries of CV districts can be seen more clearly with six equally divided and magnified parts in Appendix A.

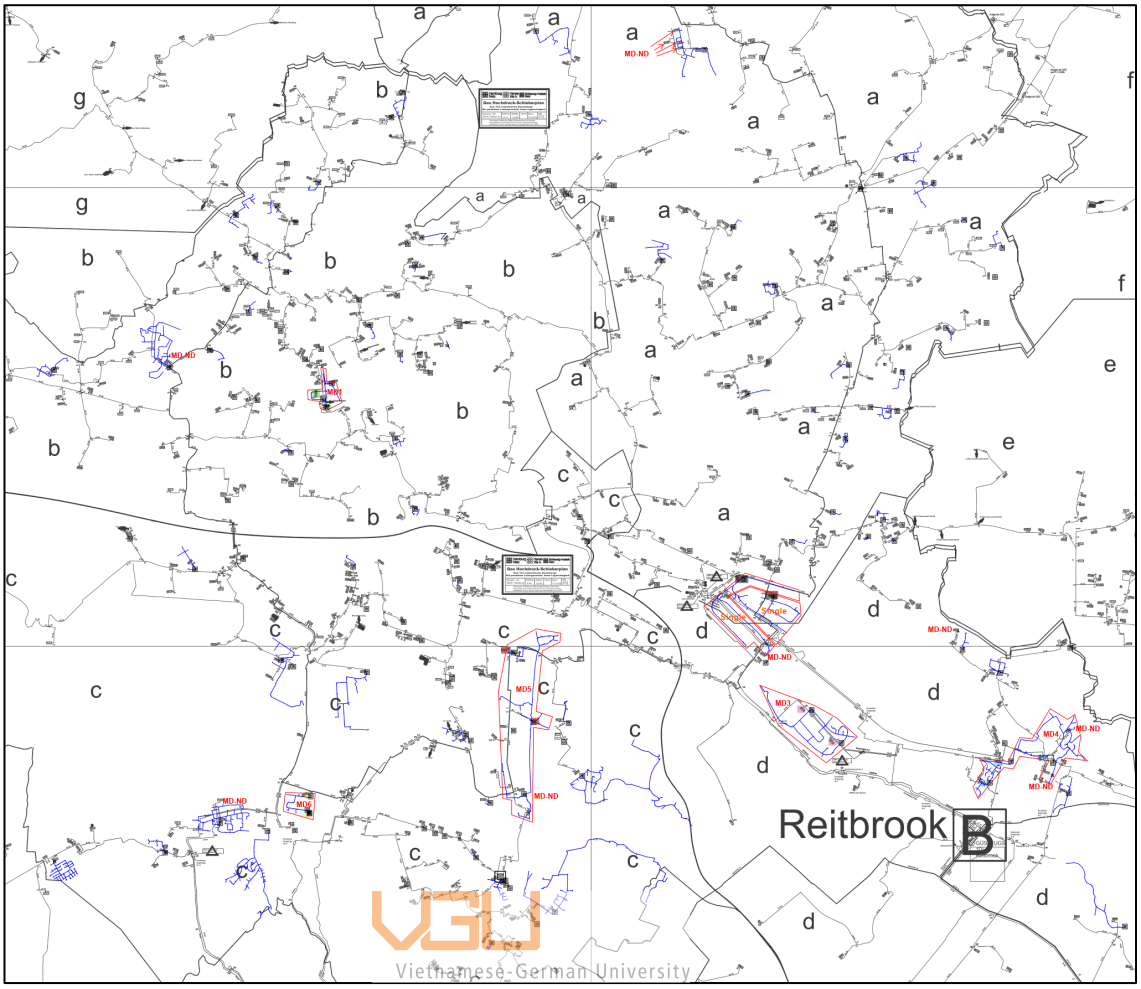


Figure 3.2 The medium-pressure network. (Blue line) [13]

The MD grid receives gas from the HD grid and supplies it to customers that directly connect to it and/or to the ND grid. When the ND grid receives gas from the MD grid, a so-called “MD-ND” area is formed. These “MD-ND” areas are maintained in the new division of the downstream grids as it is less expensive to feed gas into the ND grid from the MD grid than from the HD grid. The feed-in controllers to the “MD-ND” areas belong to the MD grid and can be part of multi-sided districts or single-sided districts or isolated sections.

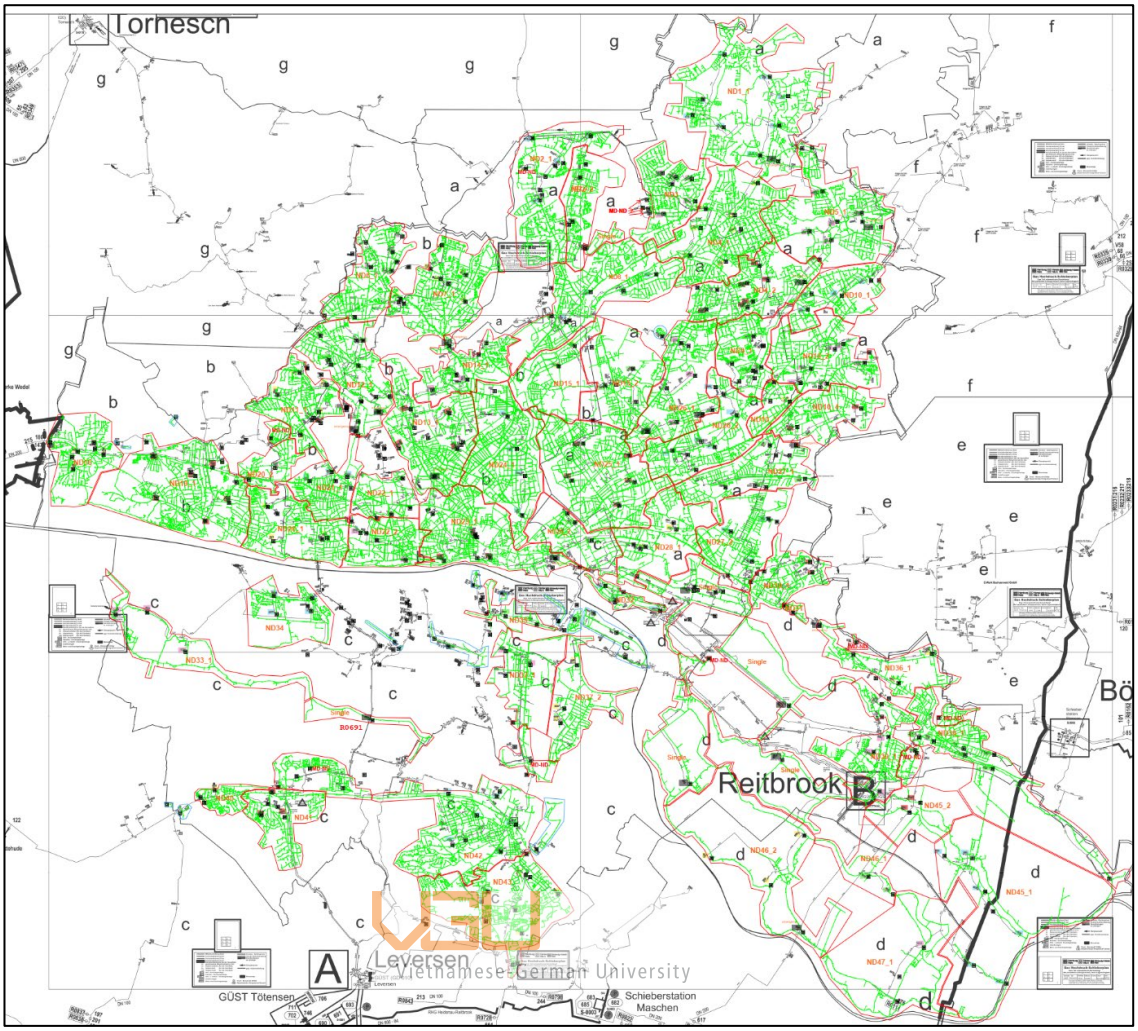


Figure 3.3 The low-pressure network. (Green line) [14]

The square symbols which can be seen in Figure 3.4 represent a controller. If there is a suffix “i” next to the ID of the regulator, it connects to a single, industrial customer. For instance, two regulators, R-0370 and R-0499i are shown. Regulator R-0370 is one of 244 regulators that feed gas into the hydraulically connected low-pressure grid. On the other hand, regulator R-0499i belongs to the other group connecting directly to an industrial customer and is completely isolated from the vast network as the customer is indicated by a small green dot.

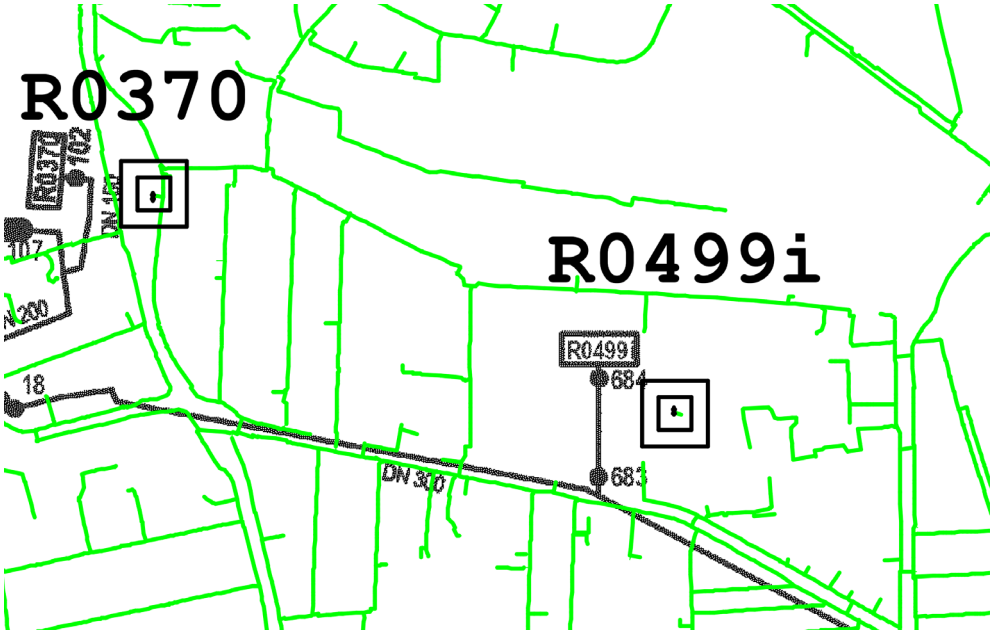


Figure 3.4 Difference between regulator connecting to the downstream grid and regulator only connecting to a single customer. [14]

It should be noted that a single-sided district is defined distinctly from an isolated downstream segment with one feed-in point. A single-sided district is a downstream section that needs to be hydraulically separated from a bigger section while an isolated segment is already separated from the major downstream grid. The gas consumption in the isolated segments is also estimated via standard load profiles. Two segments marked with blue boundaries are shown in Figure 3.5 as an example.

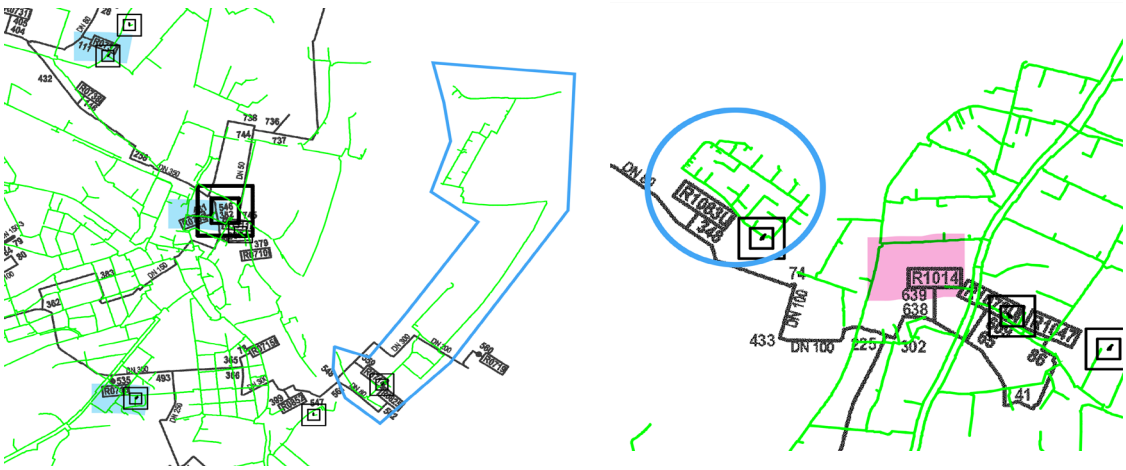


Figure 3.5 Already isolated downstream segments. [14]

4 Division of the downstream grid

The DVGW worksheet G685-2 indicates that the calorific value to be invoiced for individual exit points must be determined following its network topological position [3]. In principle, it is more practical for a network operator to use a mutual billing calorific value for multiple customers in close proximity, especially when there is no clear distribution of the downstream consumption to the pressure regulating stations that feed gas into the downstream network. The concept of calorific value districts was hence developed. A calorific value district is defined as a network section where all customers are invoiced with the same calorific value [15]. One or more exit points can be allocated to a CV district and the number of CV districts depends on the size and complexity of the network. In case a CV district is supplied by only one pressure regulating station, the regulator is called a single-sided feed-in and the district is referred to as a single-sided district. On the other hand, when a downstream section is supplied by more than one regulator, the district has a multi-sided supply.

In the prior study on gas quality tracking in the city gas grid of Hamburg, the downstream low-pressure and medium-pressure grids were tentatively divided into fifty-four virtual CV districts, three of which are single-sided. In the area where the grid has a high degree of meshing, some lines or pipes with low volume flow rates had to be cut virtually so that as little gas as possible flows across the boundaries of the CV districts. The flow information was given in Stanet under a given steady-state hydraulic situation.

In this study, the CV districts and their boundaries are reconsidered under the assumption that these districts may be in reality hydraulically separated by the gas grid operator Hamburg. The improvement of calorific value determination is taken into account so that the “2 % - limit” rule of DVGW code G 685-2 is ensured even when a large amount of gas with different quality (i.e. hydrogen) is injected into the grid.

4.1 General procedure

Assigning exit nodes where the pressure regulating systems feed gas into the major downstream grid to a CV district is an iterative process. Each iteration of the arrangement of the calorific districts is evaluated using a variety of H_2 scenarios. As a starting point, hydrogen is assumed to be admixed with natural gas immediately before entering the regional distribution network from its entry nodes. Additionally, in each scenario, the

network receives the admixture of natural gas and hydrogen from only one entry node. This simplification assures that the hydrogen concentration would never exceed an assumed limit. When there is a “2 % - limit” violation in one or more districts, the districts shall be re-examined until the corresponding calorific value deviations reduce to a minimum. The overall result should ensure compliance with the “2 % limit” in most of the scenarios and most of the months over the investigating period because of seasonal fluctuations in gas consumption.

4.2 Sorting the exit nodes into calorific value districts

The ND map with tentative district boundaries is mostly used to establish the new division of the downstream grid due to its high complexity and the high number of CV districts. The map includes regulators supplying gas to the meshed low-pressure network, directly to big industrial customers, or to already isolated downstream segments. It is crucial to identify the regulators supplying gas to the hydraulically connected grid on the map because only they are relevant to the division process. From the viewpoint of the high-pressure grid, the regulators are placed at the exit nodes, but from the viewpoint of the downstream grid, they are considered feed-in points. Hence, these two words will be used interchangeably from now on. All the network topology data are available digitally in Stanet.

There are two factors affecting the decision of choosing which exit nodes of the HD grid belong to which CV district. The first factor is their position in the HD grid which has a big impact on the gas quality, hence the compliance with the “2 % - limit”. The second factor is the way the pressure regulating stations at these exit nodes connect to the downstream grid. For example, if a regulator cannot supply gas to most of the customers in a CV district because the distances from the regulator to the customers are long or there are too few pipes connecting the regulator to other parts of the district, then the regulator shall be considered not suitable for the district. In the following, the procedures for the two factors are described.

4.2.1 Examination from the perspective of the high-pressure grid

The geometry of the high-pressure network has a considerable impact on the gas quality distribution as can be described in the following. From the result of the first simulation where no hydrogen is injected into the grid, the calorific values at the neighboring exit

nodes seem to be nearly similar. The flow situation is not yet considered in this stage because the flow direction may vary with time and by different scenarios. Therefore, the groupings of these feed-in points are classified into three categories according to their position in the grid. The three categories have different levels of certainty that their calorific value will be similar and are as follows:

Category 1: Exit nodes of a CV district lie on one branch.

Category 2: Exit nodes of a CV district lie on multiple branches. These branches are connected to a mutual distribution line. Additionally, there are no pipes transferring the gas into or out of the distribution line between these branches.

Category 3: Exit nodes of a CV district lie on multiple branches or hypothetical branches. These branches are connected to a mutual distribution line. The nodes lying on hypothetical branches must be located near the distribution line so that they can be assumed to have the same gas quality. Additionally, gas may flow into or out of the distribution line through the hypothetical branches.

Several terms are made up to describe the grouping process easier. A “branch” is defined as one of the parts of the HD grid that is connected to a distribution pipeline at only one point. Gas flows into a branch can only distribute to the exit nodes on the branch or travel back to the main pipeline when there is an oscillating zone at the point of connection. Meanwhile, a “hypothetical branch” is different from a normal branch in the fact that there is no dead end on the hypothetical branch; gas can continue to flow through the hypothetical branch to other parts of the grid. Figure 4.1 shows an example of two normal branches and a hypothetical branch. Regulator R-0433 and regulator R-0436 each lie on a branch, while regulator R-0486 lies on a hypothetical branch and is located near the distribution line.

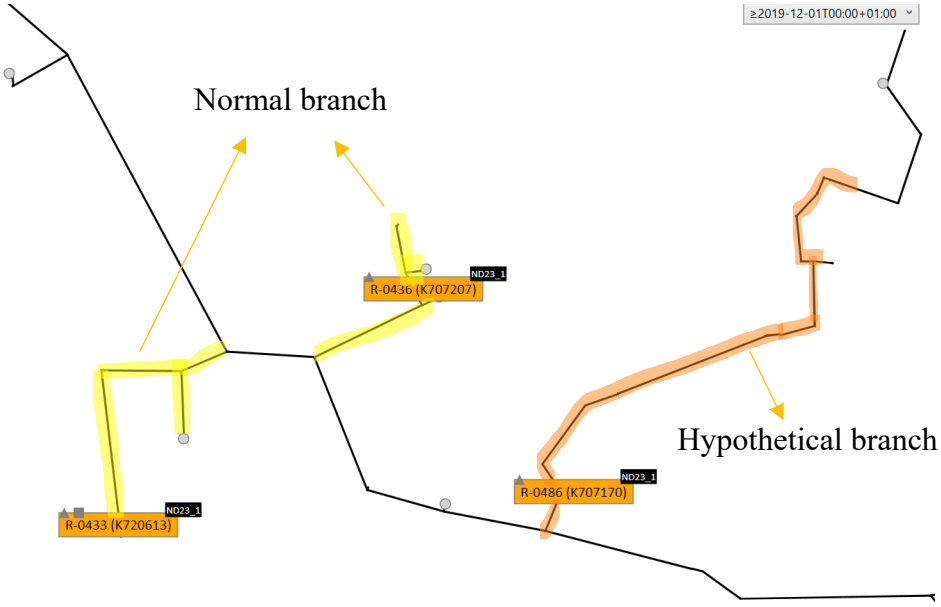
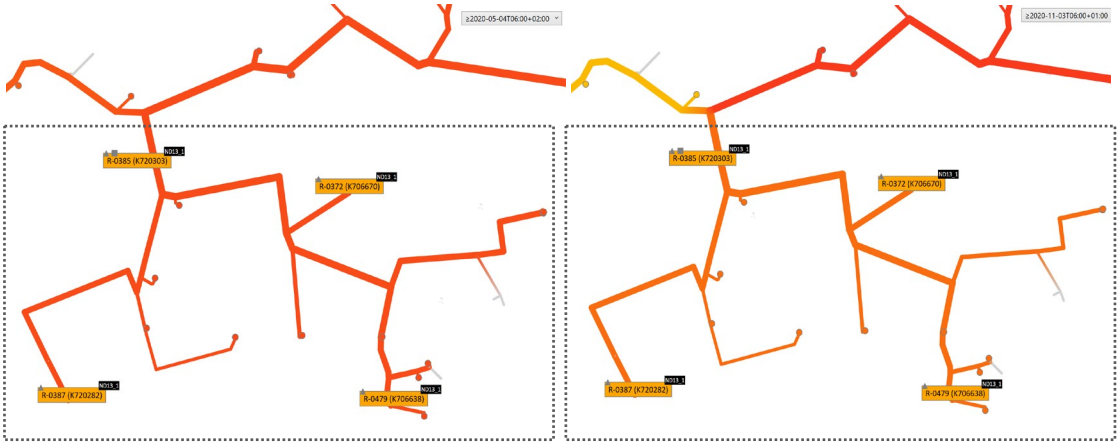


Figure 4.1 Difference between a normal branch and a hypothetical branch. A magnified part of the HD grid of Hamburg.

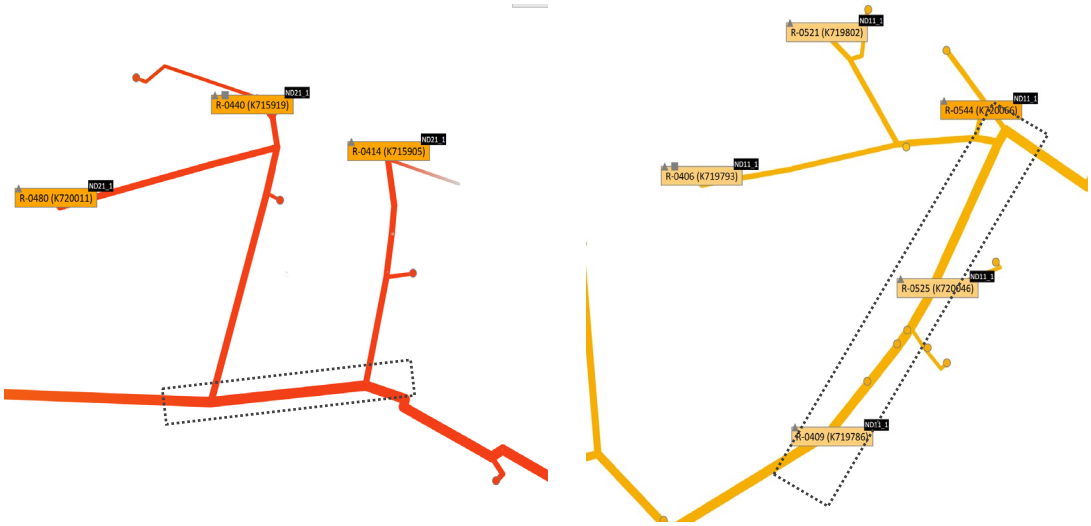
Category 1 is considered the best case in which the calorific values of the district's exit nodes are certain to be almost the same. Figure 4.2 illustrates category 1 with an example of district ND13_1 in two months, June and December, to demonstrate that the certainty of having a similar calorific value at the exit nodes is highest in the three categories no matter how the gas flows before entering the branch. District ND13_1 has five exit nodes, one of them is treated as an emergency feed-in and provides no gas to the downstream grid during the period under investigation, thus it would not be shown here in the figure the four other nodes lie on one branch. The gas flow rate in June is lower than in December due to the temperature difference and hence the consumption difference. It can be seen that the flow in the distribution line transferring gas into the branch in June is steadier, indicated by one color along the line. In December, the line receives gas with different qualities from two ends, indicated by two colors yellow and red; however, when gas enters the branch, the quality becomes stable again. In both months, the calorific values of the four exit nodes are the same and can be seen by the same orange color along the branch.



(a) Flow situation in June (b) Flow situation in December

Figure 4.2 Districts belonging to category 1. (ND13_1)

The certainty of the exit nodes of a CV district having a similar calorific value in category 2 is lower than the one in category 1 because they can have different fractions of entry volume. However, as long as these branches are located near each other, there may be no difference or very insignificant difference in calorific value, and hence the exit nodes can be grouped into one district. Category 2 is illustrated by two examples, ND11_1 and ND21_1 in Figure 4.3. District ND21_1 has three exit nodes, two of which lie on one branch and the other exit node lies on another branch; district ND11_1 has three branches and five exit nodes. All these branches are connected to a mutual distribution line which is marked by a rectangle in the figure and there are no other pipes in between these branches transferring gas into or out of the mutual distribution line. However, it is still possible that there are branches without any exit nodes belonging to a CV district to be in between these concerned branches as shown by district ND11_1.



(a) District ND21_1 (b) District ND11_1

Figure 4.3 Districts belonging to category 2.

Even though the calorific values at exit nodes in category 3 have a lower certainty to be similar compared to category 1, the CV districts classified as category 3 still comply with the 2 % - rule in most of the scenarios. As an extension of category 2, an exit node of the concerned CV district can lie on a pipeline that does not have a dead end. Therefore, gas can travel from a different part of the grid via this pipeline into the mutual line, leading to a slight difference in calorific values between the nodes; or gas can travel out of the mutual line via this pipeline. One essential condition for category 3 to work is the exit nodes lying on the hypothetical branches must be located near the mutual line in order to have a similar calorific value with other exit nodes. Figure 4.4 describes category 3 with an example of district ND7_1. Five out of six exit nodes of the district lie on normal branches, and only one exit node (K706106) lies on a hypothetical branch that is connected to another part of the grid.

Figure 4.4 District belonging to category 3.

There are possibilities that a CV district is defined but does not belong to any of the three categories mentioned above. The nearby exit nodes of these CV districts would have similar calorific values but may also vary slightly, depending on the flow situation of the scenario they are simulated. Another remark is their positions relative to the entry nodes. If the exit nodes are located near an entry node, the gas is not yet mixed with gases coming from other sources and the gas quality at these exit nodes would be similar. Yet, even when this is the case and a bigger district with more feed-in points could be created, it will not be done if the consideration of the second factor is not reasonable.

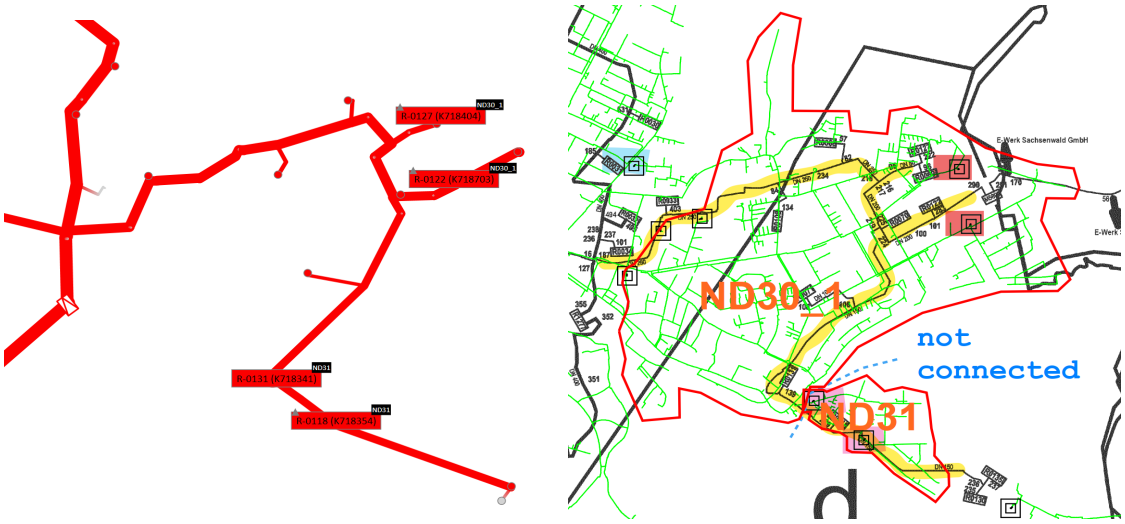
4.2.2 Examination from the perspective of the low-pressure grid

The second factor relates to the way the regulators provide gas to the downstream grid. The borders of the districts are also defined in parallel with the examination of the second factor because they are closely connected. Several criteria are used for assessing the validity of sorting the regulators and the formation of new borders.

Firstly, a CV district should have at least two feed-in points, so that if one of the regulators is defective or requires maintenance, the gas supply to consumers is still ensured. Secondly, based on the original borders of the districts on the map, the distances of the furthest consumers away from the feed-in points are roughly estimated so that they are

not too long. Customers at the furthest locations from the feed-in points may not receive gas if the consumption is too high, and the capacities of the district's regulators have reached their maximum. When the distances are too long, a regulator from another district nearby those customers may be included in the district concerned or a new border may be defined. This also helps to ensure a continuous supply for all consumers even when the temperature goes low, and the gas demand increases. Thirdly, the way the new borders are created must ensure as few pipes as possible are crossed so that the gas exchange between two "neighbor districts" is minimum. Moreover, this is practical if the CV districts may be, in reality, hydraulically separated by installing valves between the pipes. Finally, the number of pipes connecting parts of a district is also investigated. The borders can be shifted so that the customers within a district are more closely connected. For example, one part of an original district is connected to the rest by only one pipe, but it is connected to another neighboring district by multiple pipes; the border can be shifted in this case.

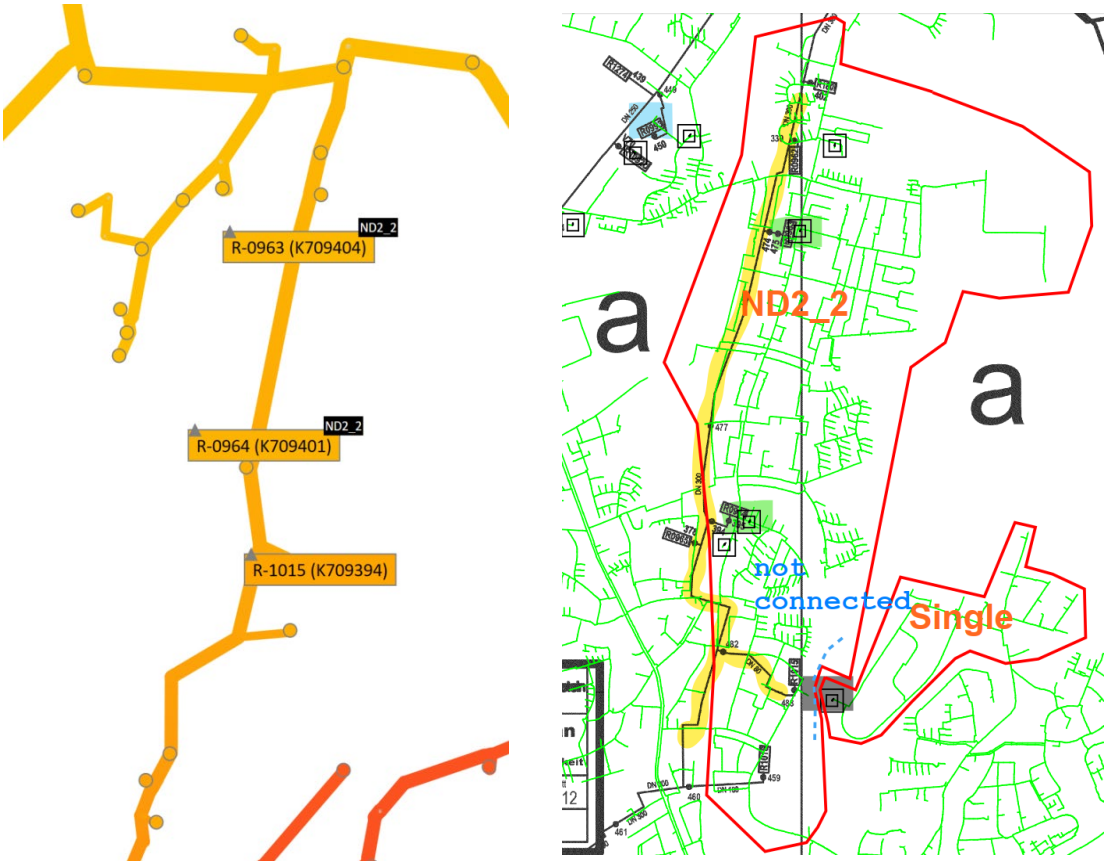
Figure 4.5 shows how the procedure is carried out with an example of districts ND30_1 and ND31. To differentiate the regulators connecting the HD grid with the ND grid from the regulators connecting the HD grid directly to customers, they are highlighted with colors. Moreover, there is a total of five colors to distinguish the regulators in different districts. There are two feed-in points in district ND30_1 highlighted in red, and two feed-in points in district ND31 highlighted in pink. The calorific values of gases from the four feed-in points would be similar because they are located on one branch (category 1) which is also marked in the figure. Nonetheless, when examining the low-pressure grid carefully, it can be seen that there is a disconnection between the two parts, resulting in the formation of two distinct districts. Two regulators of district ND30_1 do not supply any gas to the consumers in district ND31, so gathering the four regulators into one district does not make it fair and reasonable in the billing process. This is to emphasize that careful attention should also be paid to the connection of the downstream grid.



(a) HD perspective (b) ND perspective

Figure 4.5 First example of the examination from the downstream perspective. The downstream districts ND30_1 and ND31 are hydraulically separate from each other.

Another example is given below in Figure 4.6. The examined regulators are two feed-in points of district ND2_2 colored in green, and the single-sided supply colored in gray. At first glance of the HD grid, the three regulators would make a perfect category 2 because they are all located on nearby branches and receive gas from a mutual line highlighted in yellow. However, the gray regulator supplies gas to a section of the ND grid that is separate from the section behind the two green regulators. That is why these three regulators cannot be gathered into one CV district as well. The reason why the gray regulator is treated as a single supply instead of being grouped into another district will be discussed in chapter 4.3.



(a) HD perspective (b) ND perspective

Figure 4.6 Second example of the examination from the downstream perspective.
District ND2_2 and a single-sided district are hydraulically separate from each other

4.3 Exit nodes that do not belong to a multi-sided district

Several pressure regulating stations cannot be treated as feed-in points of a multi-sided district because of the difference in the calorific values and their locations of injection into the downstream grid. In these cases, there are two possibilities to utilize the regulators depending on the level of meshing of the downstream section behind them. An exit node of the HD grid that does not belong to a multi-sided district can be treated as a single feed-in of a single-sided district or as an emergency feed-in to the district it is meshed with. The use of single-sided feed is usually not preferred due to insecure reasons, for example, when the regulator or the pipe connecting the regulator and the district is defective or maintained. Thus, when both options are reasonably possible, the emergency feed-in will be used instead.

4.3.1 Emergency feed-ins

Emergency feed-ins refer to exit nodes of the HD grid that are inappropriate to be part of a CV district and also connect to an extremely meshed downstream area. Emergency feed-ins mean that the regulators here only supply gas in some specific periods, e.g., when there is a high demand for gas and the rest of the regulators in the district do not have enough capacity. This can be realized by setting the pressure level of the emergency regulators at a low value. Emergency feed-ins have been considered as a possible measure to ensure the energy billing complies with the regulation of DVGW G685 in the previous study [11]. The measure is shown schematically in Figure 4.7. In the figure, the width of the line illustrates the quantity of gas fed into the downstream district A, and the thin red line indicates there is no gas flowing through the emergency feed-in regulator.

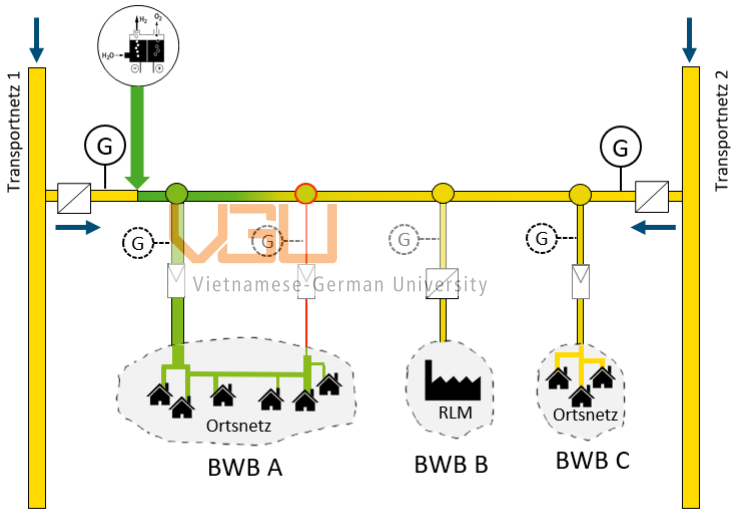
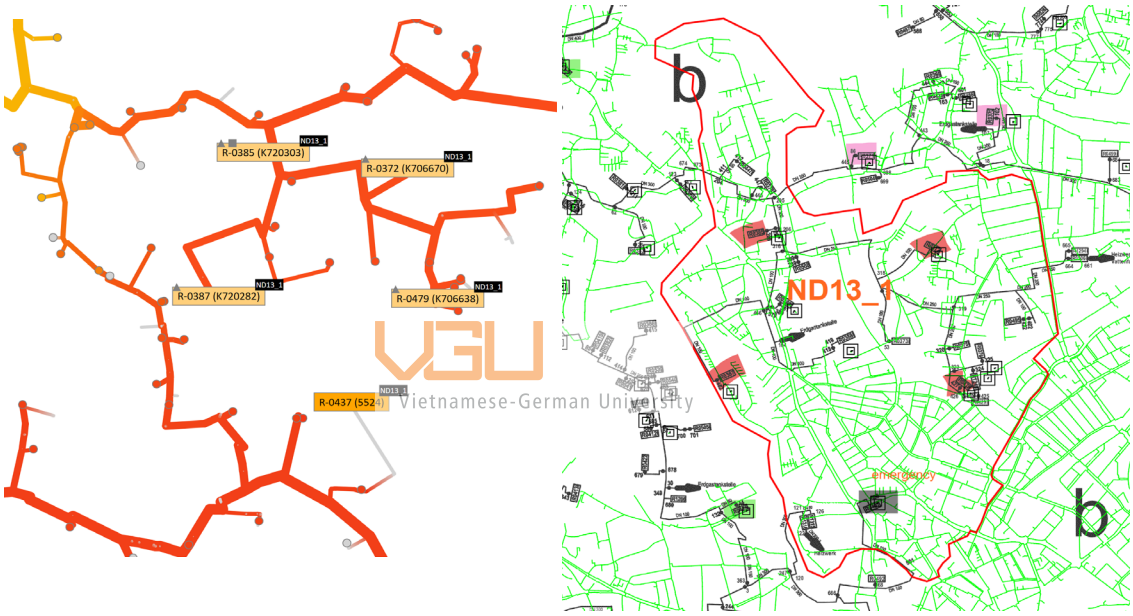


Figure 4.7 Schematic diagram of emergency feed-ins. [11]

In this study, it is assumed that the emergency regulators do not supply gas to the downstream region throughout the whole investigating period for the sake of simplicity and consistency. Furthermore, the regulators are still assigned to the CV district that they are connected to, and the allocation of gas volume offtake is done via the node weight in SmartSim (Chapter 4.4).

District ND13_1 is again shown in Figure 4.8 to illustrate the reason why a regulator is considered an emergency feed. To explain this better, the HD grid and the ND grid are

shown side by side. There are in total five regulators assigned to district ND13_1, four of them, highlighted in red, lie on one branch (category 1) and feed gas into the ND grid. Firstly, regulator R-0437 highlighted in gray connects to a different part of the HD grid and possibly receives gas with different compositions and properties, so it is not appropriate for district ND13_1. Secondly, the regulator is also not appropriate for the closest neighboring district (ND21_1) because the downstream section behind it is relatively disconnected from the district (see Appendix A). Lastly, since the low-pressure grid behind it has a high degree of meshing, it is not easy to cut lines and create a new border around the regulator to make it a single feed-in. For all these reasons, it is optimal to make regulator R-0437 an emergency feed-in.



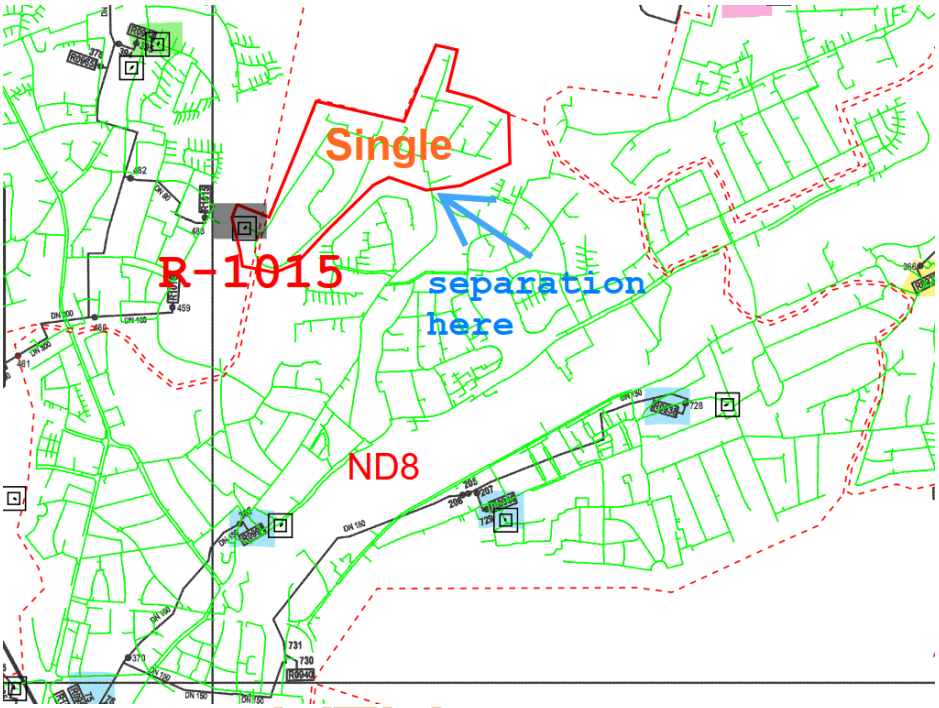
(a) HD perspective. (b) ND perspective.

Figure 4.8 An example of emergency feed-ins.

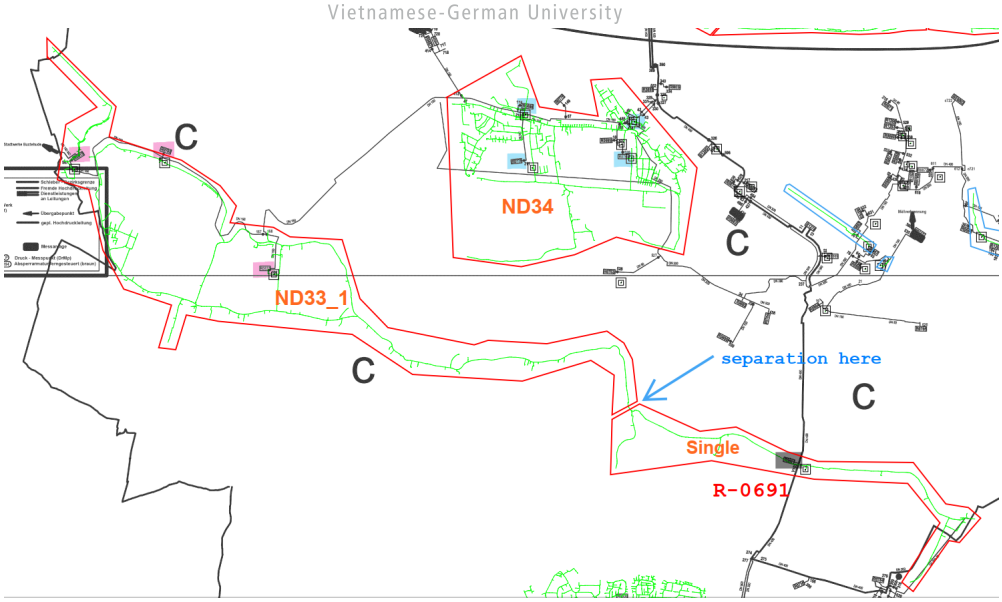
4.3.2 Single feed-ins

A controller shall be considered the only feed-in point of a single-sided calorific value district if it often has a different calorific value compared to the neighboring controllers and the downstream section it feeds gas in can be easily isolated from the major connected downstream network. This is usually the case in the southern part of the Hamburg gas grid. The low-pressure network in the south has a low degree of meshing with a limited amount of feed-ins. The controllers are usually far from one another and situated on

different branches of the HD grid, leading to a high chance of having dissimilar calorific values. Two examples of single-sided districts can be seen in Figure 4.9 (a) and (b), one district is in the northern part, and the other is in the southern part.



(a) Single-sided district separated from the original district ND8.



(b) Single-sided district separated from the original district ND33.

Figure 4.9 Examples of single feed-ins.

In Figure 4.9 (a), regulator R-1015 previously belonged to district ND8, but it does not have a similar gas quality to its neighboring regulators because it lies on a different branch

of the HD grid. The low-pressure section that it feeds gas into is not completely hydraulically separated from the other section because of only one pipe, so the grid operator can easily separate it by installing only one valve. Moreover, regulator R-1015 is also not suitable as an emergency feed-in of the original district ND8 because the distance between the nearest neighboring regulator of ND8 and the consumers in the isolated section is long. Therefore, the best option is to treat R-1015 as a single feed-in of its own district. In Figure 4.9 (b), district ND33_1 and the single-sided district supplied by R-0691 are also connected via only one pipe and completely hydraulically separate from the rest of the grid. There are four feed-in points to this section. Three regulators of district ND33_1 are located in close proximity and on the same HD branch while regulator R-0691 receives gas from another part of the HD grid and is located far from the other three. The distance between the three regulators and the furthest customer within the original district ND33 would be very long if R-0691 were treated as an emergency feed-in. For these reasons, R-0691 is also treated as a single supply node.

4.4 Assignment of the downstream consumption

As mentioned in Chapter 2.1.2, the standard load profile calculates the energy demand of a downstream network. Accordingly, the total amount of gas used by unmetered customers is known. In SmartSim, the so-called “node weight” is used to allocate the offtake volumes to the individual exit points within a section. The calculated SLP energies and the measured RLM volumes are then distributed proportionally to the node weights. It should be noted that a “section” is a hydraulically connected downstream network supplied via several exit points, while a “calorific value district” can have some other nodes besides the nodes of a section. However, in this project, the calorific value districts are the same as the sections, i.e., the nodes belonging to a district get the same designation as a section.

4.4.1 Customer values assignment

In the previous study, the customer values [kWh] are assigned to a single representative node of a district, then the SLP volumes are calculated and distributed equally to all the nodes within the district via node weight. Since the exact outflow at individual regulators is unknown, the assumption that each regulator within a district is assigned the same exit volume is reasonably adequate. For this study, the customer values are manually and

equally assigned to all exit nodes belonging to the CV districts from the previous study in the beginning. As a result, when the division of the downstream network is modified after each iterative simulation, less effort is needed to reassign the customer value.

The exit nodes chosen as emergency feed-ins shall be excluded from the assignment of customer values because the emergency feed-ins are assumed to provide no gas throughout the studied period. Furthermore, since the emergency feed points are still assigned to the CV district they are meshed with, they are given zero weight with regard to node weight. For single feed-ins, they are allocated an equal amount of customer factors as the exit nodes of the multi-sided CV district they all once belonged to. The exit nodes treated as single supply do not have any node weight.

4.4.2 RLM customers assignment

For measured volumes of a CV district, they are first summed up and then also equally distributed to all the exit nodes of that district via node weight. Unlike the customer values for SLP customers, the RLM volumes of industrial customers are already assigned to specific exit nodes and are not supposed to be changed. The data is in MSCON format, and the assignment is done by mapping the industrial customers' ID to the nodes' ID. However, there are several situations that an exit node of a CV district assigned RLM customers are considered emergency feed-ins. If that is the case, the RLM customers will be reassigned to another random node of the district. The fact that the measured volumes are also distributed evenly via node weight emphasizes that it does not matter which node of the district should be assigned the RLM customers. Doing this will not guarantee total accuracy, but it facilitates the process as finding the address of the industrial customers and matching them to the regulator stations based on the downstream map would be burdensome.

4.5 Result of the simulations and discussions

4.5.1 Scenarios for hydrogen injection

To see the result of the new downstream division, six scenarios where hydrogen is well mixed with natural gas at each of the six network interconnection points before distributing in the network are used. The limit value of hydrogen is chosen to be 20 % by volume as this is a potential limit target. In these scenarios, the energy of the gas mixture

at the injection point is maintained to be the same as the energy of natural gas without hydrogen so that the energy balance in the entire network is still correct. The admixture of hydrogen in natural gas reduces the calorific value and standard density of the gas mixture. Hence, the new hourly properties of the mixture are calculated as the sum of 80 % of natural gas' original value and 20 % of hydrogen's value. The mixture volume is then achieved by dividing the original input energy by the new calculated calorific value.

Table 4.1 shows an overview of the six scenarios at six respective network interconnection points as well as the results of the first simulation where the new division of the downstream grid has not been yet applied. There are multiple violations in the "2 % limit" in the first simulation, especially where the feed-in flow rate of hydrogen is high. In the scenarios Ohe Twiete, Reitbrook Ring, Reitbrook Zentral, the hydrogen admixture is distributed throughout the northern part of the grid. There are many CV districts established there because of the high degree of meshing. Consequently, most districts are critical in these three scenarios. Even though the feed-in flow rate of hydrogen is highest in the Tötensen scenario (19,000 m^3/h), the admixture is mostly distributed throughout the southern part of the grid, where fewer CV districts are established. Hence the number of violations in this scenario is moderate, in nine districts. There are fewer violations in Leversen and Mehal Rückeinspeisung because the average amounts of H_2 input at these two locations are much lower (3,900 m^3/h at Leversen and less than 500 m^3/h at Mehal). In this chapter, the detailed results for scenarios at Tötensen and Ohe Twiete will be given as two typical examples, and the overall result will be summarized to check the validity of the downstream division.

Table 4.1 Overview of H_2 scenarios (at entry nodes).

NKP	Average H_2 feed-in flow rate (equivalent to 20 % of the total input volume at the location)	NO. of districts violating before the new division of the downstream grid
Tötensen	19,000 m^3/h	9
Leversen	3,900 m^3/h	2
Ohe Twiete	12,000 m^3/h	17
Reitbrook Ring	14,200 m^3/h	16
Reitbrook Zentral	5,400 m^3/h	17
Mehal Rückeinspeisung	< 500 m^3/h	0

4.5.2 Tötensen

The network interconnection point Tötensen is located in the southern part of the grid where the main consumption is from industrial customers (Figure 3.1). The investigating period is from February to December 2020. The corresponding feed-in quantity of hydrogen for this scenario is 19,000 m^3/h. The compliance with the "2 % limit" is evaluated for all the CV districts. Table 4.2 (a) and (b) provide two overviews of the calorific value district reports in the investigating period. They compare the detailed results of the first simulation with previous CV districts and the simulation using the latest version of the downstream division. The largest deviation of a feed-in calorific value belonging to a district from the volume-weighted calorific value of that district is shown for every district and every month. The values are highlighted in three colors to clarify the check for conformity with the DVGW G685 billing rule. If the deviation is less than 1 %, it is highlighted in green. The increased deviations from 1 % to 2 % are highlighted in yellow. If the values are higher than 2 %, indicating the violation of the "2 % rule", they are highlighted in red.

It can be seen that the result of the new downstream division is very positive. When using the old downstream division, nine out of fifty-one calorific districts do not comply with the 2 % limit according to the DVGW G 685. The most critical districts are M-5991 with 10.38 % deviation in July and ND33 with -8.14 % deviation in August. These two districts are located in the southern part of the grid, so they receive more gas with different qualities, i.e., hydrogen, resulting in a higher calorific value deviation. In fact, district M-5991 is not relevant for the investigating purpose because there is no downstream grid behind its regulating stations. The exit nodes are grouped into one CV district because only the total exit volume of the regulators of the district is measured, not the individual one. The distribution of the gas offtake to each regulator is done via the node weight. Other critical districts are located in the lower northern part of the network. Since the feed-in quantity from Tötensen is large, the hydrogen mixture also enters this area and creates a big difference in the nodal caloric values of these districts. The new division of the downstream grid improved the determination of the billing calorific value for compliance with the technical rule as there are no critical districts anymore (Table 4.2 (b)).

Table 4.2 Overviews of the district reports from February to December 2020 – Tötensen. H_2 is admixed at Tötensen with an average quantity of 19,000 m^3/h (green values are below 1 %, yellow values are between 1 % and 2 %, and red values are above 2 %; analogously for negative values).

District	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12
M-5991/M-5893	6.95	7.56	9.82	6.98	7.77	10.38	9.22	7.82	9.02	7.8	7.58
MD1	0.08	0.14	0.19	0.13	0.23	0.09	0.09	0.18	0.14	0.09	0.05
MD2	0	0	0	0	0	0	0	0	0	0	0
MD3	0	0	0	0	0	0	0	0	0	0	0
MD4	0	0	0	0	0	0	0	0	0	0	0
MD5	0	0	0	0	0	0	0	0	0	0	0
MD6	1.16	1.09	0.57	1.1	0.28	0	0.02	0	0	0.6	1.02
ND1	-0.67	-0.45	-0.79	-0.44	-0.16	-0.2	-0.12	-0.22	-0.17	-0.29	-0.06
ND10	0	0	0	0	0	0	0	0	0	0	0
ND11	-0.21	-0.07	0.14	-0.16	-0.76	-0.3	-0.03	-0.85	-3.07	0.1	0.23
ND12	-7.94	-7.43	-5.81	3.31	-3	-2.84	-1.74	-3.05	-6.65	-7.33	-8.03
ND13	-1.63	-1.64	-1.82	-1.15	-2.34	-1.99	-1.29	-1.86	-1.39	-1.2	-1.78
ND14	-1.51	-1.82	-2.61	-1.57	-2.3	-1.93	-1.2	-1.73	-1.82	-1.65	-1.65
ND15	0	0	-0.01	0.01	0.12	0.14	0.26	0.02	0	0	0
ND16	0.02	0.02	0.01	0.02	-0.2	0.37	-0.07	0.75	0.93	0.01	0.02
ND19	0.01	0	-0.01	-0.01	0.59	1.07	0.19	2.17	2.63	-0.01	0
ND2	0	-0.02	-0.45	-0.46	-0.23	0	0	0	-0.02	-0.01	0
ND20	0	0	-0.05	-0.12	-1.11	-1.69	-1.01	-1.92	-0.73	0.03	0
ND21	-0.11	-0.26	-0.95	-0.76	-0.22	-0.44	0.06	-1.44	-1.98	-0.63	-0.1
ND22	3.36	2.51	1.28	0.59	0.07	0.18	0.04	0.25	1.99	2.73	3.84
ND23	2.28	2.37	2.02	1.23	2.23	2.17	1.36	1.89	1.58	1.38	2.2
ND24	0	0	-0.01	0	0.01	0.02	0.04	0.01	0	0	0
ND25	0	0	0.01	0	0.03	-0.01	0.02	0	0	0	0
ND26	0.01	-0.01	-0.28	-0.23	0.11	0	-0.01	0	-0.15	-0.1	0
ND27	0	0	0	0	0	0	0	0	0	0	0
ND28	0	-0.01	-0.27	-0.25	-0.15	0	0	0	-0.14	-0.09	0
ND3	0	0	-0.05	0.02	-0.04	0	0	0	0	0	0
ND30	0	0	0	0	0	0	0	0	0	0	0
ND31	0	0	0	0	0	0	0	0	0	0	0
ND32	0	0	0	0	0	0	0	0	0	0	0
ND33	0.08	0.07	0.07	-0.01	-3.62	-6.16	-8.14	-4.75	-0.25	0.05	0.06
ND34	0	-0.01	0	-0.02	-0.02	-0.03	-0.07	-0.05	-0.01	-0.01	-0.01
ND35	0	0	0	0	0	0	0	0	0	0	0
ND36	0.01	0	0	0	0	0	0	0	0	0.01	0
ND37	0	0	0	0	0.01	0	-0.01	0	0	-0.01	0
ND38	0	0	0	0	0	0	0	0	0	0	0
ND39	0	0	0	0	0	0	0	0	0	0	0
ND4	-0.78	-0.67	-0.78	-0.66	-0.25	-0.28	-0.26	-0.31	-0.19	-0.32	-0.06
ND40	0	0	0	0	0.03	0	0	0	0	0	0
ND41	0	-0.01	0	0	0.02	0	0	0	0	0.01	-0.01
ND42	0.01	0.01	0.02	0.01	-0.09	-0.01	0.02	0	0	0	0.03
ND43	0	0	0	0	-0.02	0	-0.01	0	0	0	0
ND44	0	0	0	0	0.01	0	0	0	0	0	0
ND45	0	0	0	0	0	0	0	0	0	0	0
ND46	0	0	0	0	0	-0.01	0	0	0	0	0
ND47	0	0	0	0	0	0	0	0	0	0	0
ND5	-0.4	-0.3	-0.14	-0.05	-0.22	-0.29	-0.31	-0.33	-0.12	-0.11	-0.08
ND6	0	0	-0.24	-0.64	-0.04	0	-0.07	0	-0.21	-0.03	0
ND7	-0.31	-0.34	-1.22	-0.84	0.78	-0.01	0.19	-0.01	-0.19	-0.19	0
ND8	0.96	0.81	0.89	0.56	0.2	0.05	0	0.22	0.36	0.45	0.1
ND9	0.01	-0.01	-0.31	-0.29	-0.19	0.01	-0.01	0	-0.16	-0.11	0

(a) Overview of the district reports before the application of the new downstream division.

District	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12
MD1	0.07	0.1	0	0.05	0.28	0.11	0.09	0.15	0.05	0.01	0.04
MD3	0	0	0	0	0	0	0	0	0	0	0
MD4	0	0	0	0	0	0	0	0	0	0	0
MD5	0	0	0	0	0	0	0	0	0	0	0
MD6	1.16	1.1	0.57	1.1	0.28	0	0.02	0	0	0.6	1.02
ND1_1	0	0	-0.01	-0.02	0	0	0	0	0	0	0
ND10_1	0	0	0	0	0	0	0	0	0	0	0
ND10_2	0	0	0	0	0	0	0	0	0	0	0
ND10_3	0	0	0	0	0	0	0	0	0	0	0
ND10_4	0	0	0	0	0	0	0	0	0	0	0
ND11_1	-0.12	-0.05	-0.04	-0.1	-0.21	0	0.02	0	-0.45	-0.05	-0.07
ND12_1	0	-0.02	1.13	0.92	-0.03	0	0.01	0	0.24	0.21	0
ND13_1	0	0	0.01	0.01	0.01	0	0	0	-0.01	-0.01	0
ND14_1	0	0	0	0	0	0	0	0	0	0	0
ND15_1	0	0	0	0	0.01	0.09	0.03	0.03	0	0	0
ND15_2	0	0	0.01	0	0.01	0	0.03	0	0	0	0
ND16	-0.02	-0.02	0.01	0.01	-0.2	0.42	-0.09	0.82	0.9	-0.01	-0.02
ND19_1	-0.03	-0.03	-0.01	-0.01	0.37	0.66	0.14	1.34	1.46	-0.02	-0.03
ND2_1	0	0	-0.08	-0.13	0.06	0	0	0	0	0	0
ND2_2	0	0	0.09	0.09	0.05	0	0	0	0.01	0.01	0
ND20_1	0	0	0	0.02	0.08	0.31	0.15	0.47	0.27	0	0
ND20_2	0	0	0	0	0.22	0.66	0.15	0.99	0.42	0	0
ND21_1	0.17	0.33	0.42	0.12	0.08	0.13	0	0.1	0.9	0.59	0.12
ND22_1	1.23	0.73	0.37	0.14	0.05	0.13	0.03	0.14	0.44	0.6	1.5
ND22_2	-0.02	0	0.02	-0.01	-0.02	0	0	-0.02	0.01	0.03	-0.01
ND23_1	-0.06	0	-0.01	-0.02	-0.01	0.01	-0.02	-0.01	-0.02	0.01	-0.06
ND24_1	0	0	-0.01	0	0.06	0.08	0.18	0.01	0	-0.01	0
ND25_1	0	0	0	0	0	0	0	0	0	0	0
ND25_2	0	0	0	0	0	0	0	0	0	0	0
ND26_1	0	0	-0.01	0	0.01	0	0	0	0	0	0
ND26_2	0.01	-0.02	-0.17	-0.24	-0.06	0	0	-0.01	-0.09	-0.1	0
ND27_1	0	0	0	0	0	0	0	0	0	0	0
ND27_2	0	0	0	0	0	0	0	0	0	0	0
ND28_1	0	0	0	0	0	0	0	0	0	0	0
ND3	0	0	-0.06	-0.02	-0.04	0	0	0	0	0	0
ND30_1	0	0	0	0	0	0	0	0	0	0	0
ND31	0	0	0	0	0	0	0	0	0	0	0
ND32	0	0	0	0	0	0	0	0	0	0	0
ND33_1	0	0	-0.03	0.02	0.05	-0.04	-0.09	-0.06	-0.01	-0.02	0
ND34	0	-0.01	0	-0.02	0.02	-0.04	-0.07	0.06	0.01	-0.01	-0.01
ND35	0	0	0	0	0	0	0	0	0	0	0
ND36_1	0	0	0	0	0	0	0	0	0	0	0
ND37_1	0	0	0	0	0	0	0	0	0	0	0
ND37_2	0	0	0	0	-0.01	0	0.01	0	0	0	0
ND38_1	0	0	0	0	0	0	0	0	0	0	0
ND39_1	0	0	0	0	0	0	0	0	0	0	0
ND4_1	0	0	-0.16	-0.11	-0.1	0	0.01	0	-0.01	0	0
ND4_2	0.03	0.02	0.21	0.22	0.04	0	0.04	0	0.04	0.04	0
ND40	0	0	0	0	0.03	0	0	0	0	0	0
ND41	0	-0.01	0	0	0.02	0	0	0	0	0.01	-0.01
ND42	0.01	0.01	0.02	0.01	-0.08	-0.01	-0.01	0	0	0	0.03
ND43	0	0	0	0	-0.02	0	-0.01	0	0	0	0
ND45_1	0	0	0	0	0	0	0	0	0	0	0
ND45_2	0	0	0	0	0	0	0	0	0	0	0
ND46_1	0	0	0	0	0	0	0	0	0	0	0
ND46_2	0	0	0	0	0	0	0	0	0	0	0
ND47_1	0	0	0	0	0	0	0	0	0	0	0
ND5_1	0	0	0	0	0	0	0	0	0	0	0
ND6_1	0	0	0.1	0.28	-0.04	0	-0.07	0	0	0	0
ND7_1	0	0	-0.11	-0.28	0.02	0	-0.04	0	0	0	0
ND8_1	0	0	0	0	0	0	0	0	0	0	0
ND9_1	0	0	0	0	-0.04	0	-0.01	0	0	0	0

(b) Overview of the district reports after the application of the new downstream division.

4.5.3 Ohe Twiete

The low-pressure downstream grid is more meshed in its northern part, so more CV districts are defined here. Consequently, when hydrogen is distributed in this part, more CV districts will be critical as can be seen in Table 4.3 (a). In this scenario, the hydrogen mixture comes from Ohe Twiete with an average feed-in quantity of 12,000 m^3/h. The new downstream division again shows a big improvement as most of the CV districts no longer violate the "2 % rule", even though there are still three critical districts ND11_1, ND22_1, and ND9_1 (Table 4.3 (b)). It should be noted that not all of the newly defined CV districts have to comply with the billing regulation as the admixing of hydrogen is fictitious. For district ND11_1, the violations occur only in winter because more hydrogen is injected in these months, which results from a higher consumption. Additionally, the critical deviations also diminish with the new division from a maximum of 12 % in December for district ND11 to a maximum of 3.57 % in November for district ND11_1. Meanwhile, district ND9_1 and district ND22_1 violate the technical rule only in one month. The violations of the "2 % rule" is hence acceptable in this scenario.

Table 4.3 Overviews of the district reports from February to December 2020 – Ohe Twiete. H_2 is admixed at Ohe Twiete with an average quantity of 12,000 m^3/h (green values are below 1 %, yellow values are between 1 % and 2 %, and red values are above 2 %; analogously for negative values).

District	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12
M-5991/M-5893	-0.13	-0.1	-0.1	-0.27	-0.21	0.01	0.01	0.01	0.01	-0.04	0
MD1	0.86	1.38	1.05	0.56	0.71	0.14	0.21	0.47	1.17	1.17	0.54
MD2	0	0	0	0	0	0	0	0	0	0	0
MD3	0	0	0	0	0	0	0	0	0	0	0
MD4	0	0	0	0	0	0	0	0	0	0	0
MD5	0	0	0	0	0	0	0	0	0	0	0
MD6	0.11	0.09	0.05	0.1	0.02	0	0	0	0	0.03	0.01
ND1	5.41	5.13	5.83	5.41	0.83	0.58	0.55	1.4	5.59	7	3.99
ND10	0	0	0	0	-0.04	0	-0.03	0	-0.02	0	0
ND11	10.54	9.89	5.02	1.93	0.73	0	0.03	0	5.35	10.04	11.99
ND12	12.3	12.4	10.91	9.17	8.49	9.76	9.35	10.54	12.57	12.72	13.06
ND13	4.57	4.41	2.91	2.05	1.61	1.24	2.13	1.04	3.28	4.42	5.16
ND14	-4.3	-4.17	-2.78	-1.9	-0.29	-0.19	0.18	-0.79	-3.15	-4.18	-4.84
ND15	0	0	0	-0.02	2.64	6.34	6.19	4.89	-0.22	0	0
ND16	-0.76	-0.47	-0.19	-0.1	-0.23	0.05	-0.02	-0.21	-1.06	-0.58	-0.81
ND19	-2.12	-1.29	-0.56	-0.34	-0.62	-0.15	-0.02	-0.58	-2.83	-1.58	-2.25
ND2	0.01	0.03	1.74	2.8	0.17	0	0.03	0	0.45	0.53	0
ND20	-0.01	0	-0.01	-0.12	3	4.31	3.62	4.64	1.9	0	0
ND21	0.04	0.05	0.06	0.08	-2.76	-3.83	-4.4	-3.04	-0.4	0.02	0
ND22	-1.82	-1.25	-0.5	-0.33	-0.61	-0.55	-0.35	-0.41	-0.66	-1.01	-2.64
ND23	-0.03	-0.03	-0.03	-0.07	-0.04	0	-0.02	0	0	0	0
ND24	0	0	0	0	-0.43	-0.34	0.93	-0.04	0	0	0
ND25	0	0	0	0	-2.56	-1.28	-1.4	-0.57	0	0	0
ND26	0.01	0	0.01	0.01	1.56	0.52	0.89	0.19	0.04	0.01	0.01
ND27	0	0	0	0	0	0	0	0	0	0	0
ND28	0	0	0	0.01	0	0	0	0	0	0	0
ND3	0	0	-0.33	0.38	0.06	0	0.04	0	0.11	0.08	0
ND30	0	0	0	0	0	0	0	0	0	0	0
ND31	0	0	0	0	0	0	0	0	0	0	0
ND32	0	0	0	0	0	0	0	0	0	0	0
ND33	0.01	0	0.01	-0.01	3.2	4.54	5.24	3.63	0.4	0	0
ND34	0	0	0	0	-0.01	0.03	0.02	0.01	-0.02	0	0
ND35	0	0	0	0	0	0	0	0	0	0	0
ND36	0.01	0	0	0	0	0	0	0	0	0.01	0
ND37	0	0	0	0	0	0	0	0	0	-0.01	0
ND38	0	0	0	0	0	0	0	0	0	0	0
ND39	0	0	0	0	0	0	0	0	0	0	0
ND4	6.19	6.83	6.19	6.98	1.38	1.24	1.84	1.95	6	7.78	4.54
ND40	0	0	0	0	0	0	0	0	0	0	0
ND41	0	0	0	0	0	0	0	0	0	0	0
ND42	0	0	0	0	-0.01	0	0	0	0	0	0
ND43	0	0	0	0	0	0	0	0	0	0	0
ND44	0	0	0	0	0	0	0	0	0	0	0
ND45	0	0	0	0	0	0	0	0	0	0	0
ND46	0	0	0	0	0	0	0	0	0	0	0
ND47	0	0	0	0	0	0	0	0	0	0	0
ND5	5.99	5.62	2.41	1.29	7.79	11.35	10.38	10.57	5.42	4.29	8.53
ND6	0	0	0	0.31	-0.06	0	0.04	0	0	0	0
ND7	0.8	1.07	5.79	8.34	1.14	-0.01	0.13	-0.01	3.02	2.78	0.3
ND8	-6.46	-6.97	-6.36	-5.47	-1.41	0	-0.03	-0.09	-5.38	-7.41	-5.1
ND9	0.01	0	0.08	0.01	1.82	0.69	1.14	0.34	0.09	0.01	0.01

(a) Overview of the district reports before the application of the new downstream division.

District	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12
MD1	0.24	0.46	0.7	0.47	0.81	0.18	0.35	0.61	0.76	0.52	0.06
MD3	0	0	0	0	0	0	0	0	0	0	0
MD4	0	0	0	0	0	0	0	0	0	0	0
MD5	0	0	0	0	0	0	0	0	0	0	0
MD6	0.11	0.09	0.05	0.1	0.02	0	0	0	0	0.03	0.01
ND1_1	-0.01	0.01	-0.08	-0.1	0.04	0.01	0.01	-0.01	-0.09	-0.04	0
ND10_1	0	0	0	0	0.01	0	-0.01	0	-0.01	0	0
ND10_2	0	0	0	0	0	0	0	0	0	0	0
ND10_3	0	0	0	0	0	0	0	0	0	0	0
ND10_4	0	0	0	0	0	0	0	0	0	0	0
ND11_1	2.61	3.39	2.43	1.22	0.24	0	-0.01	0	1.76	3.57	2.46
ND12_1	0	0	-0.13	0.68	0.01	0	0.01	0	0.01	0.01	0
ND13_1	0	0	-0.03	0.03	-0.02	-0.03	-0.04	0.02	0.01	0.01	0
ND14_1	0	0	0	0	0	0	0	0	0	0	0
ND15_1	0	0	0	0.02	0.07	0	0.02	0.97	0.39	0.02	0.05
ND15_2	0	0	0	0	0.33	1.01	0.47	0.5	0	0	0
ND16	-0.47	-0.23	-0.13	-0.11	-0.23	0.07	0.01	-0.27	-1.09	-0.36	-0.5
ND19_1	-0.76	-0.37	-0.18	-0.16	-0.39	-0.11	0.01	-0.42	-1.71	-0.58	-0.8
ND2_1	0.01	0	-0.18	-0.56	-0.02	0	0.01	0	-0.05	0.05	0
ND2_2	0	0.02	0.45	0.4	0.06	0	0.01	0	0.16	0.12	0
ND20_1	0	0	0	0	0.09	0.11	0.02	-0.16	0.06	0	0
ND20_2	0.01	0	0.01	0.07	0.26	0.12	0.02	0.47	1.23	0.02	0
ND21_1	-0.02	-0.02	-0.01	-0.03	0.03	-0.01	-0.01	0.03	-0.01	-0.01	0
ND22_1	1.58	1.24	0.49	0.31	0.34	0.32	0.21	0.31	0.73	1.08	2.15
ND22_2	0	0	0	0	0	0	0	0	0	0	0
ND23_1	0	0	0	-0.01	0	0	-0.01	0	0	0	0
ND24_1	0	0	0	0	-1.16	-1.05	1.33	-0.33	0	0	0
ND25_1	0	0	0	0	0	0	0	0	0	0	0
ND25_2	0	0	0	0	0	0	0	0	0	0	0
ND26_1	0	0	0	0	-0.24	-0.01	-0.06	0.02	0.01	0	0
ND26_2	0.01	0	0	0	-0.01	-0.01	-0.04	-0.01	0	0	0
ND27_1	0	0	0	0	0	0	0	0	0	0	0
ND27_2	0	0	0	0	0	0	0	0	0	0	0
ND28_1	0	0	0	0	0	0	0	0	0	0	0
ND3	0	0	-0.34	0.39	0.05	0	0.04	0	0.14	0.16	0
ND30_1	0	0	0	0	0	0	0	0	0	0	0
ND31	0	0	0	0	0	0	0	0	0	0	0
ND32	0	0	0	0	0	0	0	0	0	0	0
ND33_1	0	0	0	-0.01	-0.11	-0.03	0.04	-0.03	-0.01	0	0
ND34	0	0	0	0.01	0	0.02	0.02	-0.01	-0.02	0	0
ND35	0	0	0	0	0	0	0	0	0	0	0
ND36_1	0	0	0	0	0	0	0	0	0	0	0
ND37_1	0	0	0	0	0	0	0	0	0	0	0
ND37_2	0	0	0	0	0	0	0	0	0	0	0
ND38_1	0	0	0	0	0	0	0	0	0	0	0
ND39_1	0	0	0	0	0	0	0	0	0	0	0
ND4_1	-0.01	0	1.18	0.8	0.49	0	-0.03	0	0.51	0.33	0
ND4_2	-0.16	-0.22	-1.39	-1.58	-0.3	0	-0.13	0	-1.3	-0.93	-0.14
ND40	0	0	0	0	0	0	0	0	0	0	0
ND41	0	0	0	0	0	0	0	0	0	0	0
ND42	0	0	0	0	-0.01	0	0	0	0	0	0
ND43	0	0	0	0	0	0	0	0	0	0	0
ND45_1	0	0	0	0	0	0	0	0	0	0	0
ND45_2	0	0	0	0	0	0	0	0	0	0	0
ND46_1	0	0	0	0	0	0	0	0	0	0	0
ND46_2	0	0	0	0	0	0	0	0	0	0	0
ND47_1	0	0	0	0	0	0	0	0	0	0	0
ND5_1	0.01	-0.01	0.03	0.01	0.01	0.05	0.15	0.03	-0.02	0.01	-0.01
ND6_1	0	0	0	-0.16	0.06	0	0.06	0	0	0	0
ND7_1	0	0	0	0.17	0.02	0	-0.03	0	0	0	0
ND8_1	-0.04	-0.04	0.02	0.02	0.03	0	0.01	0	-0.03	0.03	-0.01
ND9_1	0	0	0.03	0	2.18	0.63	1.29	0.34	0.05	0	0

(b) Overview of the district reports after the application of the new downstream division.

4.5.4 Summary of the results

The scenarios with the admixing of hydrogen at individual entry nodes have been examined. The limit value of hydrogen is chosen to be 20 % in each scenario, which results in an extreme quantity of fed-in hydrogen. Hence, the violations of the "2 % limit" rule might exist. The new division of the downstream grid has shown a noticeable improvement in the determination of the billing calorific value calculated from Eq. 2.6 regarding compliance with the billing rules according to DVGW G685. The overall result is summarized in Table 4.4 which can be used in conjunction with Table 4.1. No calculation is done for the scenario at Mehal Rückeinspeisung because it does not have any critical districts originally. In addition to the number of critical districts after applying the new division, the maximum deviation among all districts throughout the investigating period is also included for the respective scenario. Even though there are still three scenarios having critical districts, the violations just occur in some months and the maximum deviation has considerably decreased compared to the one before the new division was used. For the districts with violations, further measures should be implemented.

Table 4.4 Overview of the results of H2 scenarios (at entry nodes).

Location	Number of critical districts before applying the new downstream division	Corresponding maximum deviation before applying the new downstream division	Number of critical districts after applying the new downstream division	Corresponding maximum deviation after applying the new downstream division
Tötensen	9	10.4 %	0	1.5 %
Leversen	2	-3.8 %	0	1.0 %
Ohe Twiete	17	13.1 %	3	3.6 %
Reitbrook Ring	16	13.13 %	4	4.6 %
Reitbrook Zentral	17	13 %	1	-3.6 %

4.6 Statistics on the regulators and the calorific value districts

In case a CV district is already well established from the previous study, nothing further is done. If some modification is made, for example shifting the border of a district or changing the assignment of one regulator from a district to another, then a new CV district with a new name is created. The complete list of regulators assigned to the CV districts can be found in Appendix B.

There are in total sixty-two CV districts, fifty-seven of which are low-pressure districts and five of which are medium-pressure districts. Eighteen districts belong to category 1, twenty-eight districts belong to category 2, and eight districts belong to category 3. These categories were defined in Chapter 4.2.1. Besides, nine districts do not fall into any categories and are represented by the value 0 in the column "category" of Appendix B. Some regulators of a district can form a sub-category with a higher level of certainty that they will have a similar calorific value.

Regarding the number of regulators of the CV districts, three regulators are found to be incorrectly assigned previously during the working process. The regulator R-0460 previously assigned to district ND19 and R-0714 previously assigned to district ND42 supply gas to hydraulically isolated segments of the downstream grid (Chapter 3.2) while R-0944 injecting gas to the meshed downstream network is now assigned to district ND26_1. Eight regulators have to be classified as single feed-ins. Before there are three single feed-ins, two of them are now reassigned to multi-sided districts and one of them is still kept as a single feed-in. There are seven new single feed-ins, making the total number of single feed-ins eight. Moreover, thirteen regulators are classified as emergency feed-ins. Finally, district M-5991 can be resolved into six individual exit nodes as there is no meshing downstream (Chapter 4.5.2).

In conclusion, the total number of regulating stations feeding gas into multi-sided districts is now two hundred thirty-two including the emergency feed-ins, compared to two hundred forty-four regulators in the previous study.

5 Compliance with the limit value of hydrogen concentration

Determination of the hydrogen concentration in an existing gas network is important in terms of safety since the properties of hydrogen-natural gas mixtures are different from the properties of two individual gases. A simple and conservative methodology was developed to ensure there will be no exceedance in a certain limit of hydrogen admixture in the distribution grid, e.g., 20 %. In this chapter, the methodology is described together with its application on four exemplary locations of the grid.

5.1 Overview of the assumptions

In this study, several assumptions are made to facilitate the analyzing process and to find out the suitable method for compliance with the limit value for H_2 concentration.

The first assumption concerns the limit value for H2 concentration. Different components of gas infrastructures have different limits for the rates of hydrogen blending. In the pipelines of transmission networks at pressure levels above 16 bar, the hydrogen admixture of up to 10 % by volume can be considered unproblematic [16]. In the distribution networks, if plastic pipelines are used, hydrogen can be injected up to 100 % meanwhile the limit is 25 % if steel pipelines are used [16]. In general, a uniform limit value for hydrogen blending cannot be easily established. However, according to the conclusion of a study on the limitations of hydrogen blending in the gas grid, admixing 20 vol.-% H_2 seems to be possible from a mid-term perspective [2]. Hence, this study is carried out based on the assumption that a hydrogen concentration of up to 20 % by volume is acceptable.

The hydrogen scenarios in this chapter refer to the injection of hydrogen at any point in the HD grid. The gas flow in the considered location can either be steady – flows in one direction during the whole period, or unsteady – flows back and forth in time (pendulum or shuttle zone). The unsteady flow situation is schematically illustrated in Figure 5.1. In situations where there is an unsteady flow, it is essential to define the main direction and the reverse direction, which depend on both the time the gas travel in the reverse direction and the corresponding cumulative volumes. However, for simplification, the main direction is the direction that gas travels more than 50 % of the time.

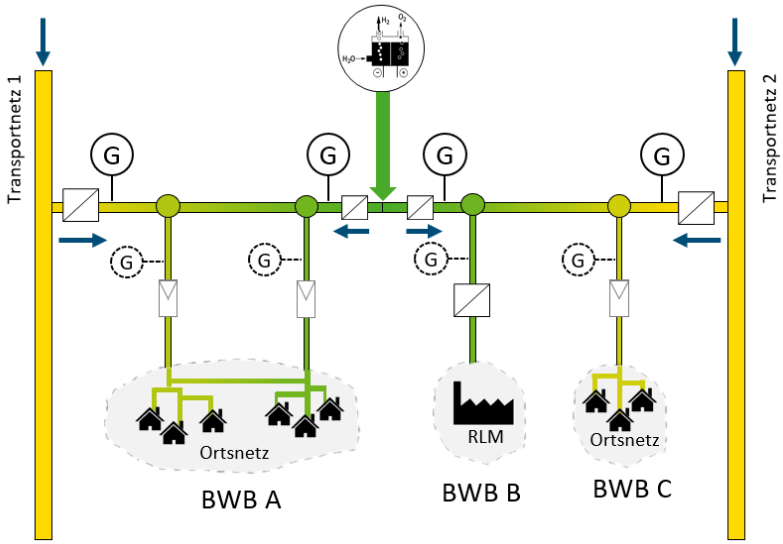


Figure 5.1 Schematic diagram of H_2 injection at any location in the grid where there is no directed gas flow. [11]

Finally, the amount of hydrogen injected at each hour is assumed to be maximal as long as the 20 % limit in H_2 content is not exceeded.

5.2 General procedure

To find out the method to ensure that the 20 % limit for H_2 concentration is not exceeded, the injection of hydrogen at a location in the HD grid with the unsteady gas flow was first examined. A proposal is to shut down the hydrogen injection when the limit is exceeded and continue the injection after a certain time period. The duration of the shutdown is based on two criteria which were determined by studying the flushing effect of hydrogen at the first location. The two criteria were then applied to different locations in the grid with different levels of unsteadiness to provide examples of suitable and unsuitable locations for injecting hydrogen.

A H_2 concentration of 20 % of the admixture corresponds to H_2 quantity of 25 % of the original natural gas volume in the pipe where hydrogen is injected. The flow situation changes after every simulation. For instance, the natural gas flow entering the pipe before mixing may decline by the presence of hydrogen, resulting in an increase in the H_2 concentration at the point of injection. To settle this problem, the amount of hydrogen is

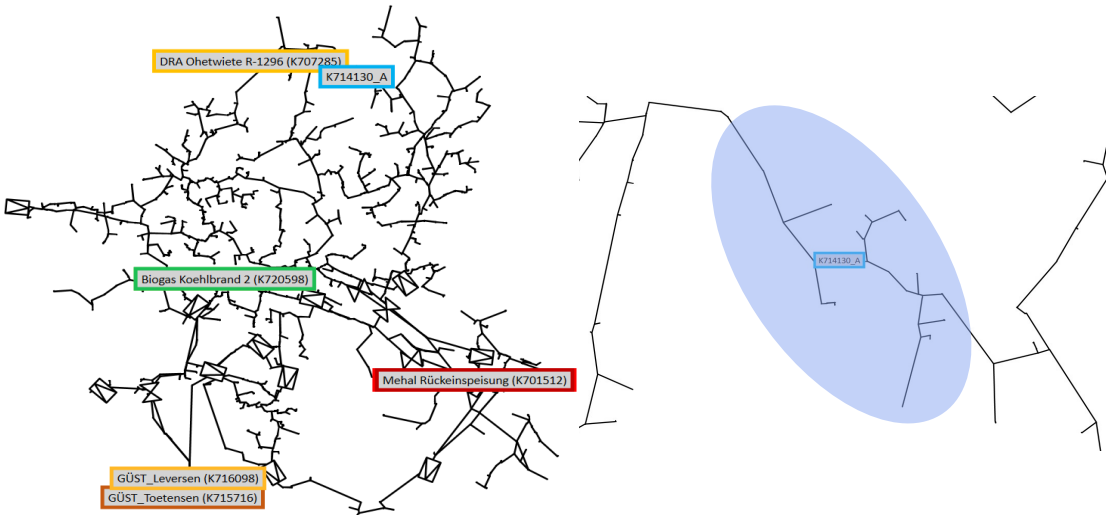
often chosen to be less than 25 % of the flow rate in the pipes investigated and is iterated several times based on the previous flow rate results.

When hydrogen is injected at arbitrary locations in the grid, the energy balance is performed slightly differently compared to the scenarios in which hydrogen is injected at the entry nodes (Chapter 4.5.1). As hydrogen is added, the total input volume increases causing an increase in total input energy. Therefore, to maintain the energy balance, the volumes of natural gas at the entry points are reduced accordingly. This reduction does not necessarily mean that the total entry volumes before and after the addition of hydrogen are also balanced, or in other words, the volume balance is traded off against the energy balance.

The reduction in entry volumes depends on the location of the hydrogen injection point. For example, if the gas flowing through the pipe where hydrogen is added comes from two sources, only the volumes at the two origins are reduced. On the other hand, if the injection point of hydrogen is somewhere in the center of the grid, gas flowing through the pipe comes from all the entry nodes during the study period, then all of the volumes at these entry nodes will be reduced. The hourly additional energy from hydrogen is divided equally to each concerned entry node, and the amount of volume reduced at each node results from the division of the equal proportion of energy reduction by the corresponding hourly calorific values of the input gas. This reduction in entry natural gas volumes, together with the presence of hydrogen itself are the reason why the flow situation changed after each simulation.

5.3 Early results

The first investigation is carried out at a location near the network interconnection point Ohe Twiete and is named location three (Figure 5.2). The injection point of hydrogen is colored blue. It is essential to define a certain area to investigate the H_2 concentration as well as the flushing effect. This area is marked in blue. The H_2 concentrations are examined for all the nodes in the area and are represented by their maximum value.



(a) Location three on the HD grid (b) The area defined at location three

Figure 5.2 Area defined at location three to study the flushing effect.

Figure 5.3 shows a good example of exceedances in the 20 % limit for H_2 concentration when an unsteady flow occurs. The period is from 15th October to 20th October. The gas flows mainly in one direction, as the volume flow during the period can be seen as mostly positive values. The red area is the original volume of natural gas without any hydrogen (before H_2 injection) while the yellow area is the volume of natural gas plus possible hydrogen when the flow is reversed (after H_2 injection). These two volumes are measured in the same pipe right in front of the H_2 injection point with respect to the main direction. The yellow area is lower than the red area because of the energy balance and the presence of hydrogen. Hydrogen is fed (blue) to the maximum every hour and the amount is slightly below 25 % of the original natural gas volume (before H_2 injection). The sum of yellow and blue areas results in the volume of the mixture in the pipe behind the H_2 injection point. The dark blue line indicates the maximum H_2 concentration in the examined area. In the first two days, the flow is steady, and the limit is not exceeded. In the next three days, there are three times that the gas flows backward with respect to the main direction. The hydrogen-natural gas mixture in the pendulum zone continuously accumulates more hydrogen from the feed-in point, causing the hydrogen content limit to be exceeded at those periods.

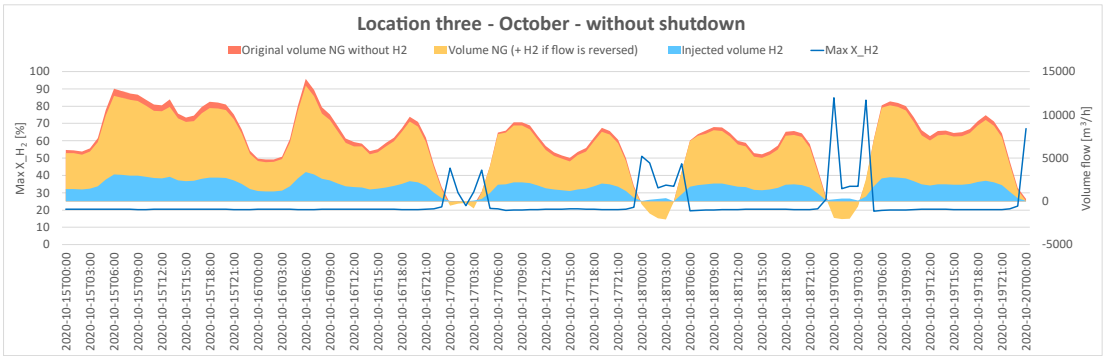


Figure 5.3 H_2 concentration with a continuous H_2 injection. The data is shown from 15th to 20th October at location three. The volumes are measured in the pipe in front of the injection point with respect to the main direction.

5.3.1 The flushing effect

The flushing effect was also studied at this location in October. Flushing in this context is used for hydrogen mixture and means waiting for all the remaining hydrogen mixture to be flushed away from the defined area by a new natural gas flow after the shutdown begins. Shutdowns of the hydrogen injection take place when the gas starts to travel in the reverse direction until all hydrogen is flushed away. An appropriate shutdown ensures the elimination of the pendulum zone before hydrogen can be injected again. To illustrate the flushing effect, Figure 5.4 shows the results of the H_2 concentration when the injection of hydrogen is stopped as soon as the flow is reversed and is continued five hours later after the gas has returned to the main direction again. The shutdown is demonstrated by the fact that the blue areas (H_2) do not exist in the three periods. The maximum H_2 content in the area dropped to zero in the few last hours of the shutdown showing that all the hydrogen admixture has been flushed away.

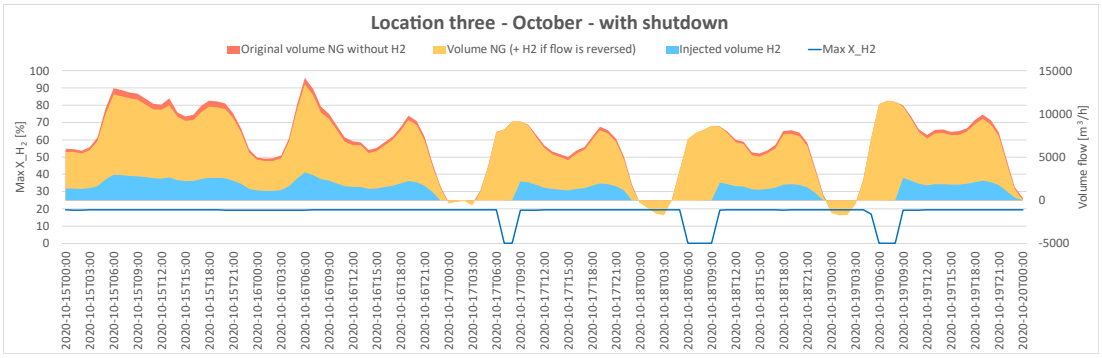


Figure 5.4 H_2 concentration with appropriate shutdowns of H_2 injection. The data is shown from 15th to 20th October at location three. The volumes are measured in the pipe in front of the injection point with respect to the main direction.

5.3.2 The criteria for the shutdown of hydrogen injection

By studying the flushing effect, two criteria have been created after many trials to ensure the hydrogen concentration of 20 % by volume will not be exceeded. The first criterion is to continue the injection five hours after the gas returns to the main direction. The second criterion is to ensure the cumulative volumes in the waiting time have reached at least five times the cumulative volumes in the reverse time. The two criteria are perceived to be conservative. In the example above, the flow is reversed in short periods (four to five hours) with low cumulative volumes compared to the cumulative volumes in the main direction. Therefore, only the first criterion is sufficient. However, when the cumulative volume in the reverse time is higher, the second criterion is required.

It should be noted that the shutdown in SmartSim takes place one hour before the flow travels in the opposite direction to get rid of any possible artifacts due to the temporal resolution of one hour. This extends the time of the overall shutdown in the study period.

5.4 Hydrogen scenarios

Four arbitrary locations in the HD grid are examined with the injection of hydrogen based on the two abovementioned criteria. These sites are referred to as “location one”, “location two”, “location three”, and “location four”, and the stability of the gas flow at these locations declines, respectively.

Location one is shown in the topology in Figure 5.5. Here, the gas flow in the pipe chosen as the injection point of hydrogen is always steady because it is located right behind a controller. The blue arrows indicate the direction of hydrogen admixture.

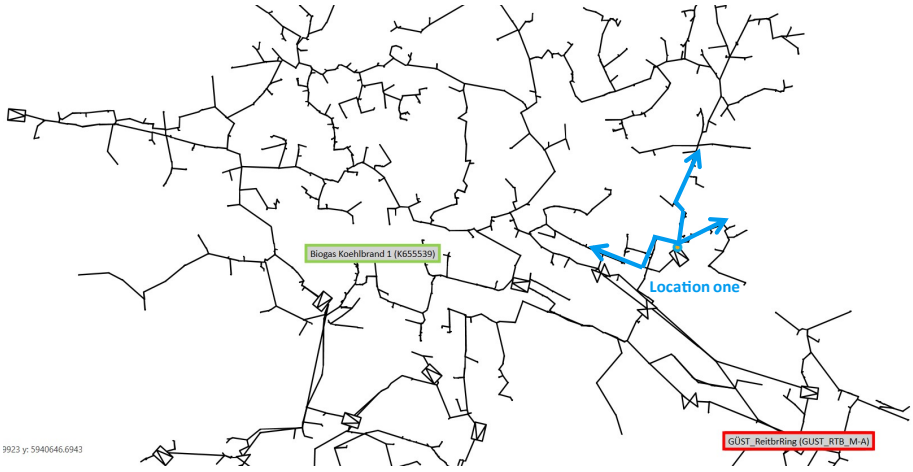


Figure 5.5 H_2 injection at location one. The gas flow is directed.

The injection at location two is in front of another controller. Here, the gas travels in the reverse direction only 2.1 % of the period under investigation with a cumulative volume of 0.4 % of the total volume flowing through the pipe. Hence, the flow at this site is considered steady most of the time. The site can be seen in Figure 5.6. The blue arrow with two ends represents the oscillating zone.

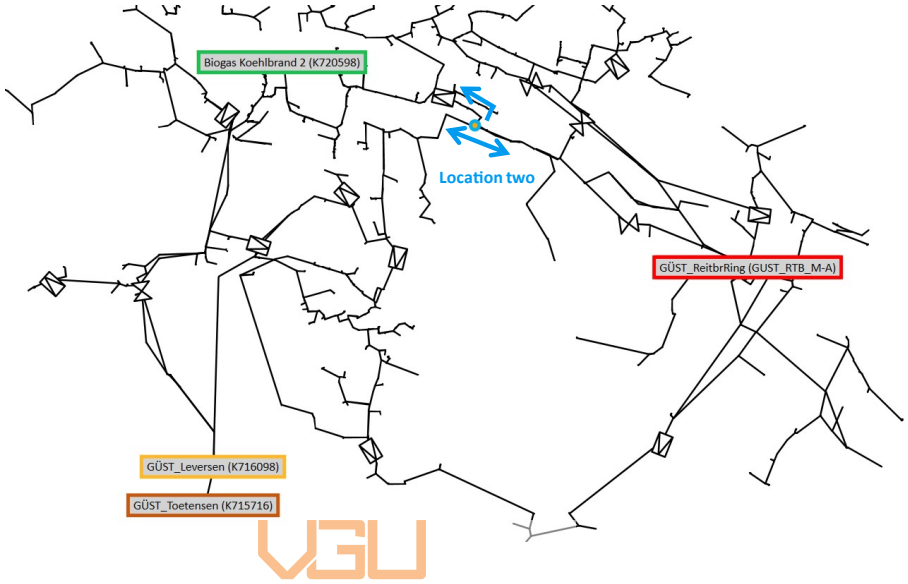


Figure 5.6 H_2 injection at location two. The gas flow is mostly directed.

The third location, location three, is near Ohe Twiete, and is also the initial site where the flushing effect was studied. From February to December 2020, gas moved in the reverse direction 8.5 % of the time with a cumulative volume of 4.1 % of the total volume. The flow situation in this location is considered quite unsteady. Figure 5.7 shows the position of hydrogen injection at location three.

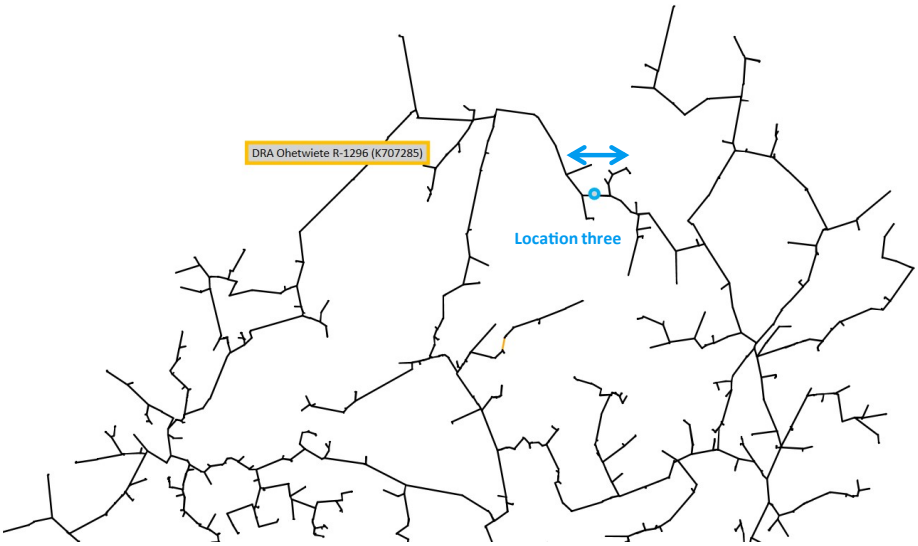


Figure 5.7 H2 injection at location three. The gas flow is slightly unsteady.

The final location, location four, can be seen in Figure 5.8. The gas travels in the reverse direction 19.7 % of the time with a cumulative volume of 11 % of the total volume, which is considered very unsteady. Remarkably, the main directions in winter and summer are different from each other. In winter, gas moves mostly to the left while in summer, gas moves mostly to the right.

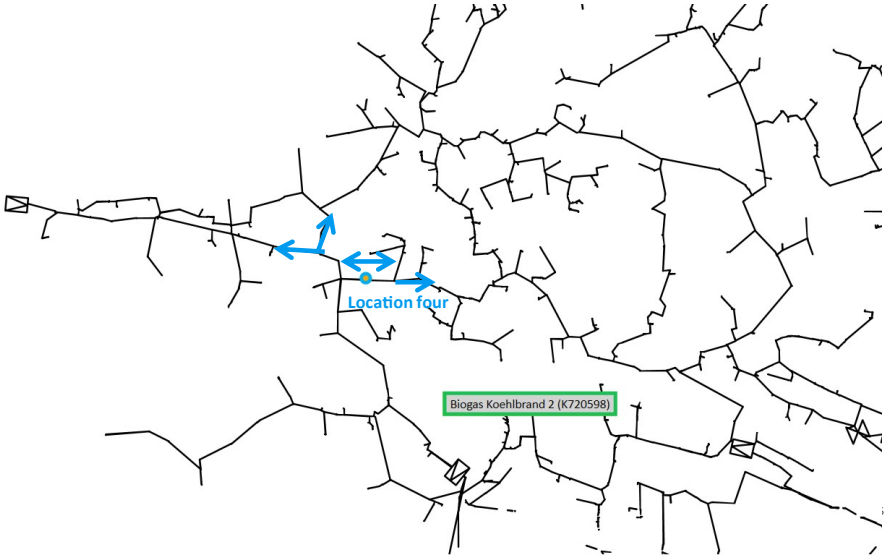


Figure 5.8 H2 injection at location four. The gas flow is highly unsteady.

5.5 Results and discussions

There is no exceedance in the 20 % limit of hydrogen admixture anymore when the two criteria for the shutdown of hydrogen injection are applied. The capacities of hydrogen feed-in at each location together with the corresponding possible injection times are best illustrated by a table. The amount of hydrogen is fixed under the period investigated and is assumed to range from 500 m^3/h to 3,000 m^3/h with a step of 250 m^3/h. For clarity, the amount of time that hydrogen can be injected is highlighted in colors. If hydrogen can be injected 95 % to 100 % of a period, the percentage is marked in dark green. Ranging from 90 % to 95 %, the percentage is marked in light green. From 85 % to 90 % of the time, it is marked in dark yellow. The light-yellow color indicates a percentage ranging from 80 % to 85 %. In case hydrogen is injected from 50 % to 80 % of the time, it is highlighted with light red color. Finally, if hydrogen can be only injected less than 50 % of the time, it is highlighted with dark red color.

Possible injection time at location one

Location one is considered the best location to inject hydrogen because the flow is always steady and there is a high flow, which corresponds to a higher amount of hydrogen to be admixed. Table 5.1 shows the possible amount of time that hydrogen can be injected every month and the year 2020 at location one. A fixed amount of 1,500 m^3/h can be constantly injected during the whole year without causing any exceedance in the 20 % limit of hydrogen in the whole grid. Even with a higher fixed amount of 3,000 m^3/h can be injected 91.4 % of the year. Furthermore, because of a higher assumption of gas in the winter months, more hydrogen can be admixed in that time.

Table 5.1 Possible injection time at location one.

	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12	Year
Reversed hour proportion	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.0%**
Reversed volume proportion	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.0%**
possible injection time	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Fixed injection H2 = 500 m3/h	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Fixed injection H2 = 750 m3/h	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Fixed injection H2 = 1000 m3/h	100.0%	100.0%	100.0%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Fixed injection H2 = 1250 m3/h	100.0%	100.0%	100.0%	100.0%	99.9%	100.0%	99.7%	100.0%	100.0%	100.0%	100.0%	100.0%
Fixed injection H2 = 1500 m3/h	100.0%	100.0%	100.0%	100.0%	99.7%	100.0%	99.7%	100.0%	100.0%	100.0%	100.0%	100.0%
Fixed injection H2 = 1750 m3/h	100.0%	100.0%	100.0%	100.0%	99.6%	100.0%	99.7%	100.0%	100.0%	100.0%	100.0%	99.9%
Fixed injection H2 = 2000 m3/h	100.0%	100.0%	100.0%	100.0%	98.5%	99.7%	98.0%	100.0%	99.9%	100.0%	100.0%	99.6%
Fixed injection H2 = 2250 m3/h	100.0%	100.0%	100.0%	100.0%	96.8%	98.3%	92.3%	100.0%	99.9%	100.0%	100.0%	98.8%
Fixed injection H2 = 2500 m3/h	100.0%	100.0%	100.0%	100.0%	90.1%	94.8%	84.9%	99.9%	99.9%	100.0%	100.0%	97.2%
Fixed injection H2 = 2750 m3/h	100.0%	100.0%	100.0%	100.0%	81.7%	89.0%	75.1%	99.6%	98.9%	100.0%	100.0%	94.9%
Fixed injection H2 = 3000 m3/h	100.0%	100.0%	100.0%	100.0%	70.8%	79.3%	61.2%	95.6%	98.7%	100.0%	100.0%	91.4%

Possible injection time at location two

Even though the flow is not very unsteady, less gas flows through the pipe at this site compared to location one, resulting in a smaller possible amount of H_2 that can be admixed. The negative sign of the percentages in the "reverse volume proportion" row illustrates that the proportion of gas flows in the opposite direction. With a fixed amount of 500 m^3/h, hydrogen can be injected 91.8 % of the year, longer in winter months than in summer months. On the other hand, if 3,000 m^3/h of hydrogen is injected, the possible time is only 21 % of the year. Table 5.2 shows the possible injection time at location two.

Table 5.2 Possible injection time at location two.

	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12	Year
Reverse hour proportion	0.6%	0.0%	0.0%	0.0%	0.4%	0.9%	6.7%	9.2%	2.4%	2.2%	0.5%	**2.1%**
Reverse volume proportion	0.0%	0.0%	0.0%	0.0%	-0.1%	-0.1%	-2.5%	-2.6%	-0.6%	-0.8%	0.0%	**-0.4%**
Possible injection time	97.3%	100.0%	100.0%	100.0%	97.9%	96.5%	81.5%	76.9%	91.8%	94.0%	97.0%	93.9%
Fixed injection H2 = 500 m3/h	96.8%	99.6%	100.0%	99.9%	94.9%	93.7%	76.1%	67.2%	91.3%	93.5%	96.6%	91.8%
Fixed injection H2 = 750 m3/h	95.8%	98.8%	100.0%	99.6%	92.5%	89.0%	66.5%	58.5%	90.2%	93.1%	96.4%	89.1%
Fixed injection H2 = 1000 m3/h	94.4%	97.0%	100.0%	99.2%	88.5%	79.3%	54.6%	48.2%	86.6%	91.7%	95.2%	84.9%
Fixed injection H2 = 1250 m3/h	93.1%	95.4%	100.0%	97.3%	83.8%	66.1%	42.7%	36.1%	81.9%	88.1%	92.9%	79.7%
Fixed injection H2 = 1500 m3/h	87.2%	91.4%	100.0%	95.4%	77.6%	52.3%	24.9%	25.1%	71.7%	82.5%	87.8%	72.3%
Fixed injection H2 = 1750 m3/h	76.6%	85.6%	100.0%	92.5%	64.9%	36.2%	10.5%	13.9%	59.7%	77.2%	80.4%	63.3%
Fixed injection H2 = 2000 m3/h	66.4%	79.4%	99.6%	88.8%	52.8%	23.4%	3.1%	7.9%	44.6%	65.6%	67.1%	54.3%
Fixed injection H2 = 2250 m3/h	51.0%	71.2%	99.3%	83.6%	44.7%	11.6%	1.9%	3.8%	32.9%	50.7%	48.9%	45.3%
Fixed injection H2 = 2500 m3/h	33.6%	61.5%	98.6%	74.5%	34.9%	4.4%	0.3%	2.1%	24.4%	34.3%	28.2%	36.0%
Fixed injection H2 = 2750 m3/h	19.3%	44.1%	96.1%	64.7%	26.3%	0.8%	0.0%	0.3%	15.6%	23.1%	13.2%	27.5%
Fixed injection H2 = 3000 m3/h	9.9%	30.8%	90.7%	51.5%	21.0%	0.0%	0.0%	0.0%	10.1%	11.8%	5.4%	21.0%

Possible injection time at location three

As the flow is quite unsteady at location three, the shutdown also occurred longer here to ensure compliance with the 20 % limit of hydrogen concentration. Moreover, the quantity of natural gas in the pipe also affects the injection time because a higher quantity of H_2 requires a higher quantity of natural gas for the admixing. A fixed amount of 500 m^3/h of hydrogen can be injected 71.6 % of the time under investigation, while a fixed amount of 3,000 m^3/h of hydrogen can only be injected 16.6 % of the time. Table 5.3 shows the possible injection time at location three.

Table 5.3 Possible injection time at location three.

	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12	Year
Reversed hour proportion	0.0%	0.0%	26.0%	28.9%	18.8%	0.0%	2.3%	0.0%	10.1%	7.8%	0.0%	**8.5%**
Reversed volume proportion	0.0%	0.0%	-12.0%	-20.7%	-29.8%	0.0%	-4.0%	0.0%	-3.5%	-1.6%	0.0%	**-4.1%**
Possible injection time	99.9%	100.0%	39.6%	31.7%	46.4%	100.0%	71.4%	100.0%	71.7%	80.8%	100.0%	76.5%
Fixed injection H2 = 500 m3/h	99.4%	98.7%	36.3%	26.3%	40.7%	88.0%	54.3%	95.8%	70.6%	78.6%	100.0%	71.6%
Fixed injection H2 = 750 m3/h	98.6%	97.2%	32.8%	22.4%	30.4%	69.1%	31.0%	83.5%	68.2%	75.3%	99.1%	64.2%
Fixed injection H2 = 1000 m3/h	96.8%	94.9%	28.3%	19.0%	16.7%	40.7%	17.3%	64.2%	63.4%	71.7%	96.9%	55.3%
Fixed injection H2 = 1250 m3/h	93.7%	92.6%	23.5%	13.4%	8.3%	17.9%	7.3%	39.6%	53.4%	67.5%	94.9%	46.4%
Fixed injection H2 = 1500 m3/h	90.7%	87.9%	17.9%	9.1%	3.8%	6.6%	1.1%	21.7%	40.4%	63.2%	93.3%	39.4%
Fixed injection H2 = 1750 m3/h	86.4%	82.9%	14.6%	5.4%	0.7%	1.3%	0.0%	10.4%	30.7%	55.4%	90.2%	34.2%
Fixed injection H2 = 2000 m3/h	81.2%	76.3%	11.8%	3.0%	0.0%	0.0%	0.0%	5.0%	20.8%	48.5%	84.9%	30.0%
Fixed injection H2 = 2250 m3/h	75.9%	67.6%	9.0%	1.6%	0.0%	0.0%	0.0%	1.4%	13.2%	41.5%	80.5%	26.3%
Fixed injection H2 = 2500 m3/h	71.3%	58.8%	7.8%	1.1%	0.0%	0.0%	0.0%	0.6%	6.4%	34.3%	75.5%	23.1%
Fixed injection H2 = 2750 m3/h	63.9%	48.2%	5.3%	0.5%	0.0%	0.0%	0.0%	0.1%	3.1%	28.5%	70.7%	19.9%
Fixed injection H2 = 3000 m3/h	56.6%	35.7%	2.8%	0.1%	0.0%	0.0%	0.0%	0.0%	1.2%	22.1%	65.6%	16.6%

Possible injection time at location four

In contrast to the situations of the three locations above, more hydrogen can be injected in the summer than in the winter at location four because the flow is more direct at that time. An amount of 500 m^3/h of hydrogen can only be injected nearly half of the year, but if the volume is 3,000 m^3/h, it is almost impossible to inject any hydrogen. This is illustrated in Table 5.4.

Table 5.4 Possible injection time at location four.

	2020-02	2020-03	2020-04	2020-05	2020-06	2020-07	2020-08	2020-09	2020-10	2020-11	2020-12	**Year**
Reversed hour proportion	23.7%	38.5%	23.6%	37.5%	3.5%	1.2%	0.5%	2.4%	19.7%	47.5%	18.3%	**19.7%**
Reversed volume proportion	-10.0%	-24.4%	-22.5%	-30.2%	-1.0%	-0.5%	-0.1%	-1.1%	-12.4%	-55.5%	-5.2%	**11.0%**
possible injection time	39.5%	16.0%	17.2%	17.2%	87.6%	95.2%	97.0%	90.3%	44.6%	6.8%	53.0%	51.4%
Fixed injection H2 = 500 m3/h	33.6%	12.7%	13.6%	16.7%	82.9%	92.3%	95.6%	88.8%	35.6%	5.1%	46.8%	47.7%
Fixed injection H2 = 750 m3/h	29.0%	10.6%	8.6%	14.0%	76.7%	88.8%	93.1%	84.6%	29.5%	2.4%	42.9%	43.8%
Fixed injection H2 = 1000 m3/h	25.0%	8.2%	3.9%	7.9%	59.3%	81.3%	87.8%	75.3%	19.5%	0.7%	37.4%	37.0%
Fixed injection H2 = 1250 m3/h	19.0%	5.1%	0.1%	3.6%	27.2%	58.2%	74.5%	52.5%	8.3%	0.0%	31.7%	25.6%
Fixed injection H2 = 1500 m3/h	12.4%	3.5%	0.0%	0.3%	6.1%	22.6%	39.1%	19.9%	1.6%	0.0%	25.4%	12.0%
Fixed injection H2 = 1750 m3/h	9.2%	1.9%	0.0%	0.0%	0.0%	0.8%	9.3%	1.4%	0.0%	0.0%	19.1%	3.8%
Fixed injection H2 = 2000 m3/h	5.7%	0.9%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	9.7%	1.5%
Fixed injection H2 = 2250 m3/h	3.3%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.2%	0.9%
Fixed injection H2 = 2500 m3/h	1.9%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.2%	0.5%
Fixed injection H2 = 2750 m3/h	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.2%
Fixed injection H2 = 3000 m3/h	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.1%

Comparison between the four locations

The overall results of possible injection time in the year 2020 in the four locations together with their total corresponding volume of hydrogen are summarized in Figure 5.9. In the figure, the fixed amount of hydrogen ranges from 500 m^3/h to 3000 m^3/h. It is easy to see the relationship between the stability of gas flow and the time hydrogen can be injected. The location from one to four are ranked in descending order of steadiness in terms of gas flow, and the possible injection time with any fixed amount of H2 also descends accordingly. Moreover, increasing the fixed quantity of hydrogen feed-in will generally reduce the possible injection time at every location because the shutdown takes place longer to ensure compliance with the H_2 blending limit.

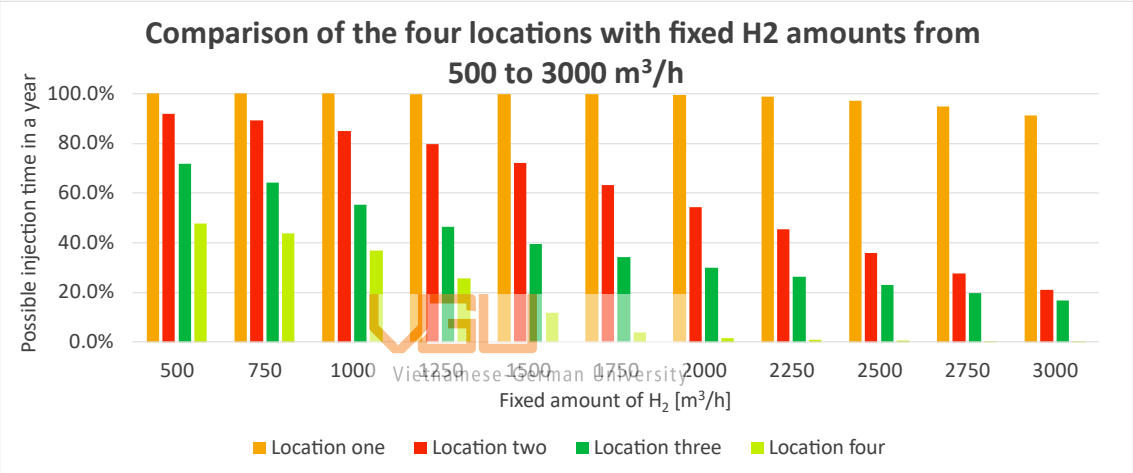


Figure 5.9 Comparison of the four locations with fixed H_2 amounts from 500 m^3/h to 3000 m^3/h.

6 Summary and outlook

6.1 Thesis' results

The thesis has addressed two aspects of blending hydrogen into the city gas grid of Hamburg.

The first aspect is about finding suitable measures to improve the calculation of billing calorific values in SmartSim in accordance with the billing rule of DVGW Code of Practice G 685-2. A proposal is studied with Smartsim, that is to re-examine the exit nodes of the HD grid Hamburg, and put them in perhaps smaller and more suitable groups, also called calorific value districts. The downstream networks of gas grid Hamburg, i.e., the low-pressure and medium-pressure networks, are then divided into calorific value districts with new borders and feed-in regulators under the assumption that these districts may be hydraulically separated by the grid operator. The procedure is iterative and includes the examination from high-pressure perspective as well as from lower-pressure perspectives. The downstream maps provided by Stanet are therefore used for the purpose. In case a feed-in is not appropriate to belong to any calorific value district, it is then treated as either an emergency feed-in or a single feed-in. The final results showed that with the new division of the downstream grids, compliance with the billing rule is met for most calorific value districts in different fictitious hydrogen scenarios. In a few scenarios, although the violation exists in several districts, the maximum deviations in the period under investigation have significantly declined.

The second part of the thesis considers the concentration of hydrogen in the grid. The H_2-blending limit is assumed to be 20 % by volume. Furthermore, on the assumption that hydrogen can be fed to a maximal limit as long as the limit is not crossed, proper criteria for the shutdown of hydrogen are established. Hydrogen can only be injected again after at least five hours since the gas returned to its main direction. The waiting time could be longer if the cumulative volume in the main direction after the return of the gas has not reached five times the cumulative volume in the reverse direction. Within the scenarios created for this task, no violation in the limit of hydrogen content is found. In addition, the two criteria can be applied to find a location in the grid suitable for the H_2 injection, especially where the gas flow could be unsteady. Another possibility is to confirm if a location is suitable for the injection with a fixed amount of hydrogen.

6.2 Evaluation and outlook

The injection of hydrogen has been studied under many assumptions in this thesis. Firstly, regarding the hydrogen concentration limit, it is assumed a 20 % H_2-blending is acceptable. In reality, the technical effort for this is high as material sensitivities of pipelines and other devices, especially regarding the reduced lifetime with the presence of hydrogen have many uncertainties. This would therefore require further investigation. Furthermore, regarding the combustion characteristics of the mixture, all the typical natural gases of the 2nd gas family, i.e., North Sea H, Russia H, Denmark H, Holland L, Germany L do not comply with the limit value for relative density when adding 20 vol.-% H_2 according to DVGW G 260. It is stated that a test for compatibility and interoperability with the gas infrastructure and the gas appliances is then needed [8]. Secondly, the flow direction of a pipe under the investigating period is chosen to be the main direction if more than 50 % of the time the gas flows in that direction. However, the cumulative volume of gas flowing in one direction can also have an influence on the choice if it accounts for a significant proportion of the total volume of gas flowing through the pipe. In the future, this factor should be considered. Finally, the time for the shutdown of hydrogen based on the two created criteria is maybe longer than the real time it needs without exceeding the 20 % limit in H_2 concentration, but it was proved to be effective and have low risk. The four locations chosen for the test of the two criteria were sufficient to compare their suitability for the injection of hydrogen depending on the steadiness levels of gas there. Nevertheless, more locations should be tested in the next research, to make sure compliance with the limit value of H_2 content is always ensured.

7 References

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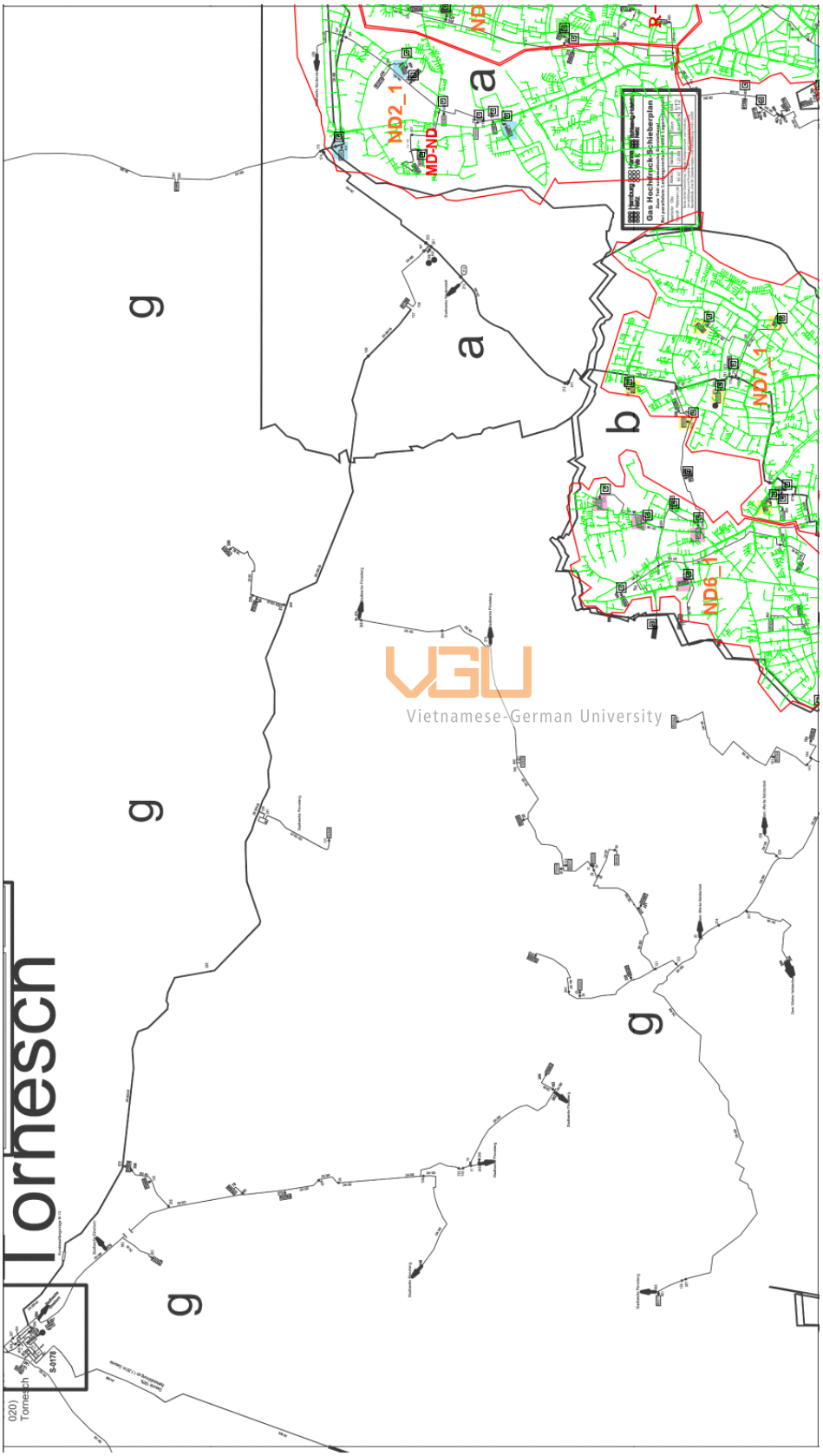
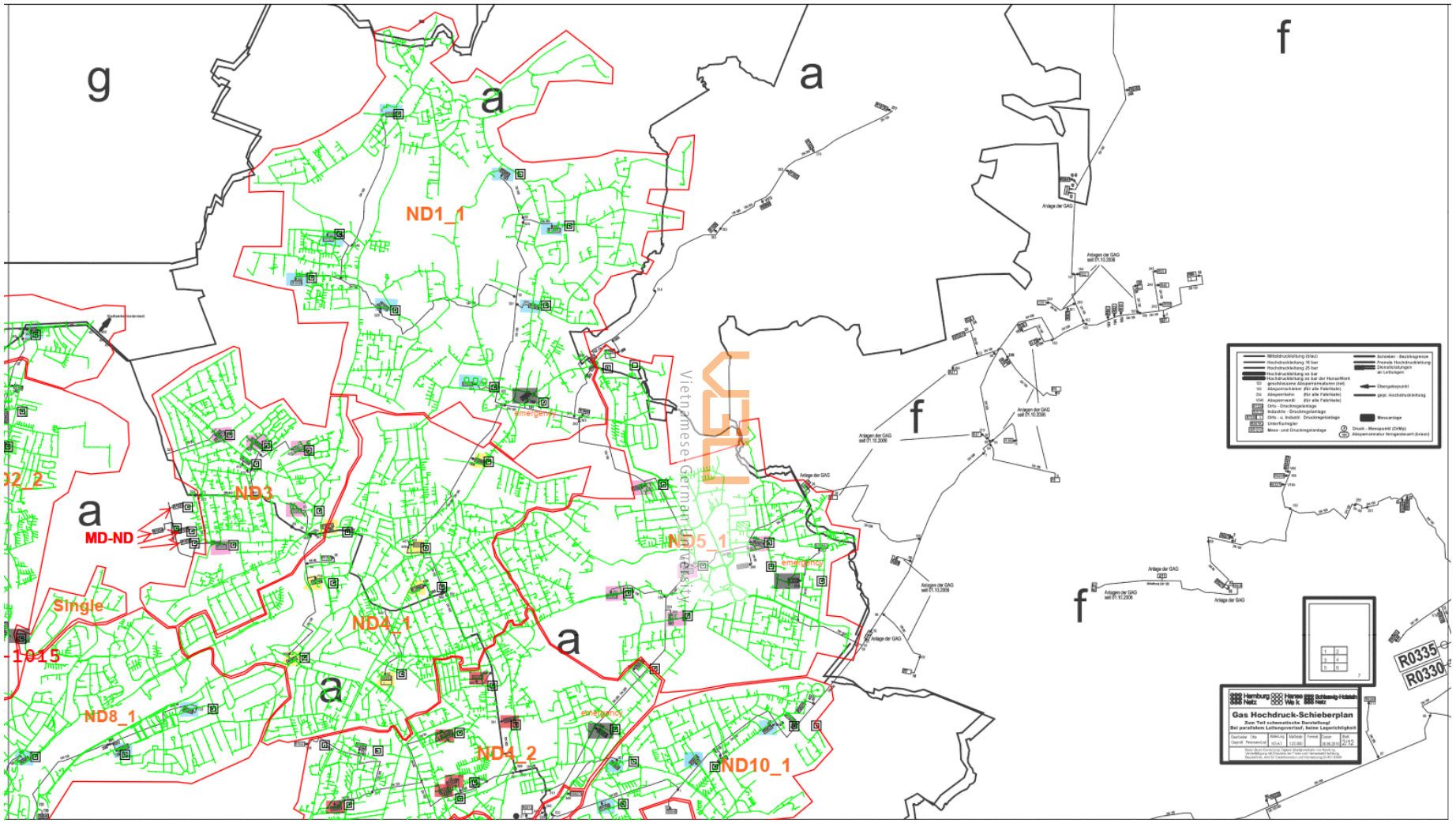
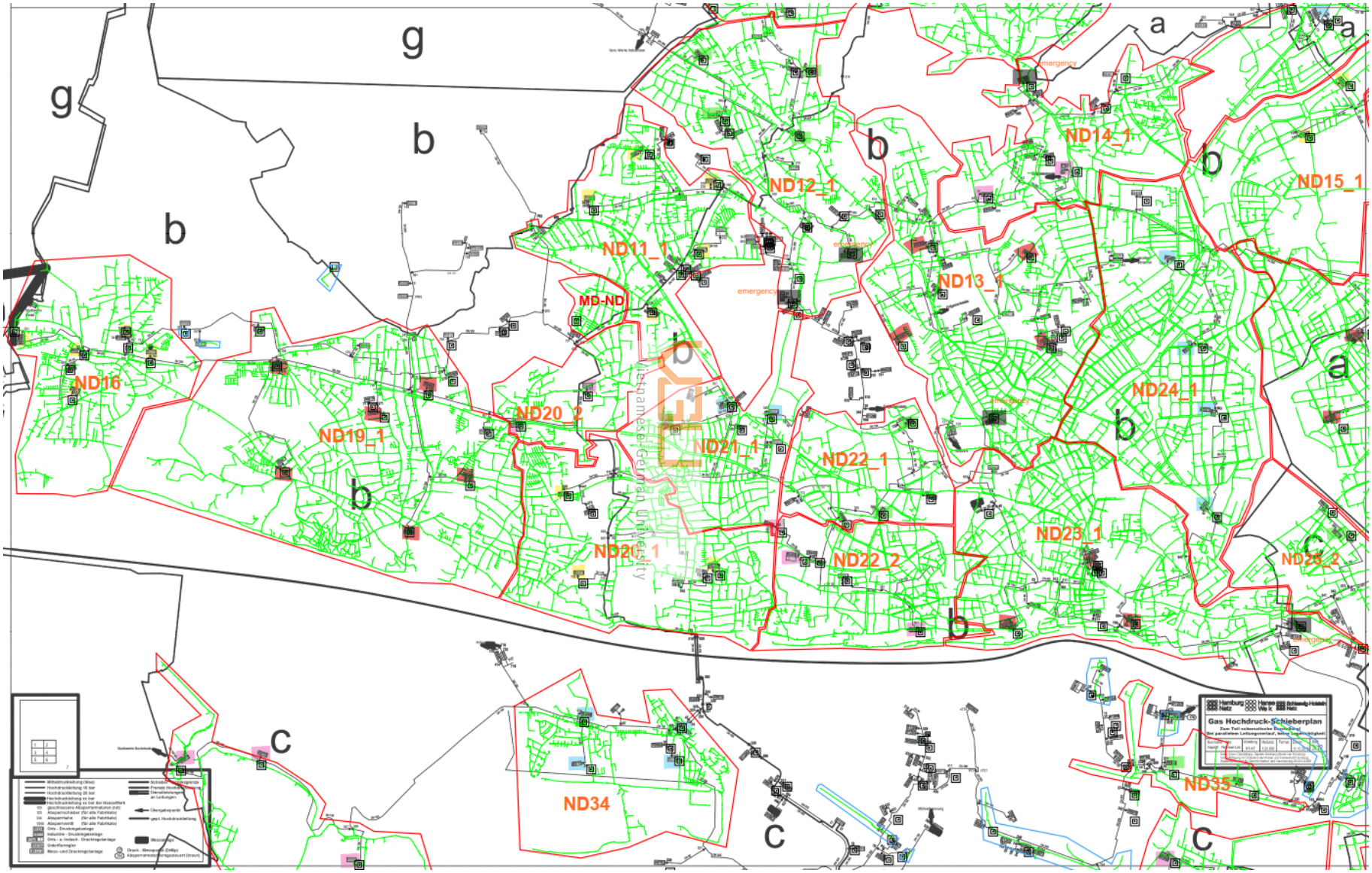
Appendix A: Low-pressure map with the defined calorific value districts



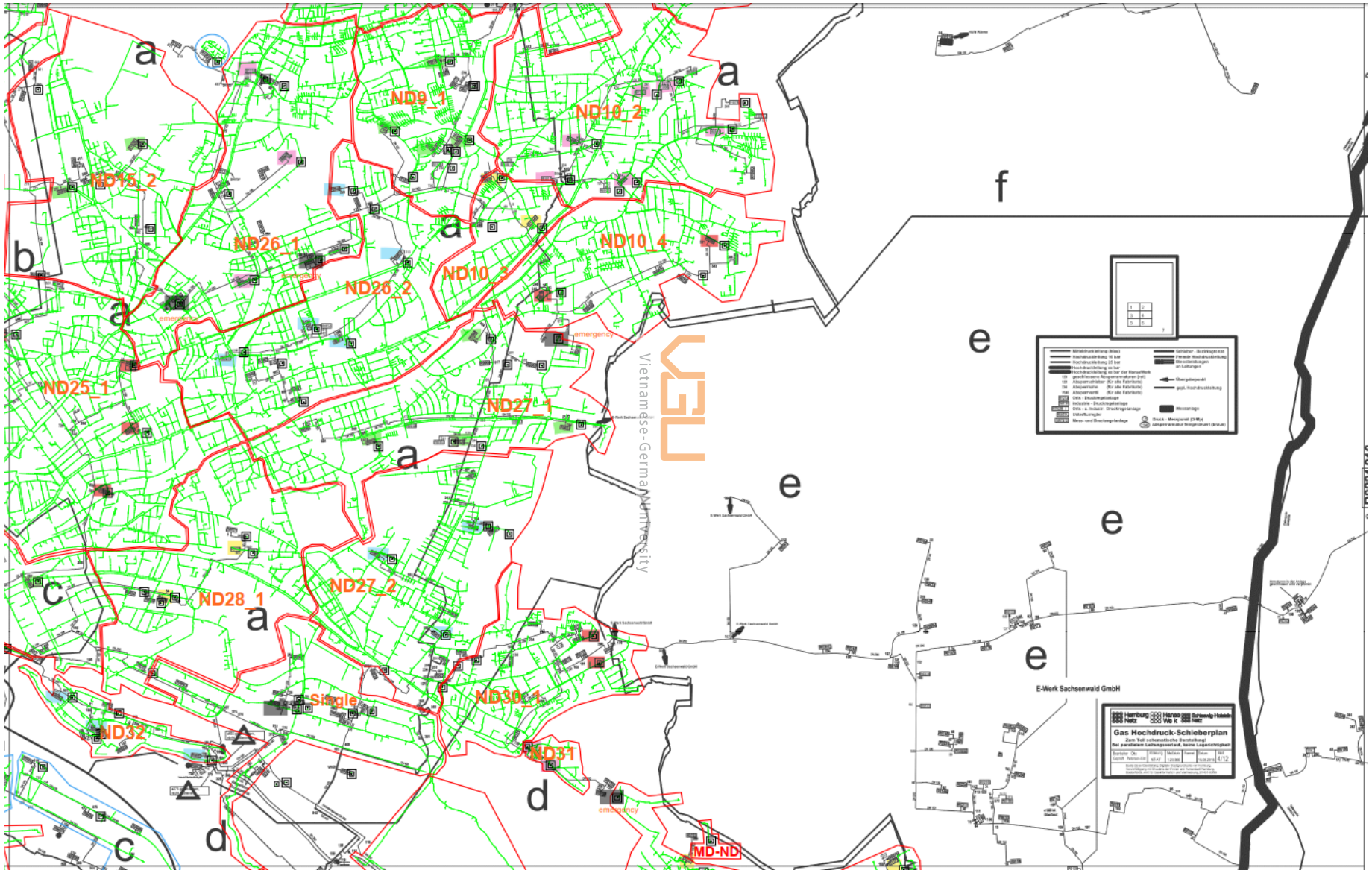
Upper-right section of the low-pressure map



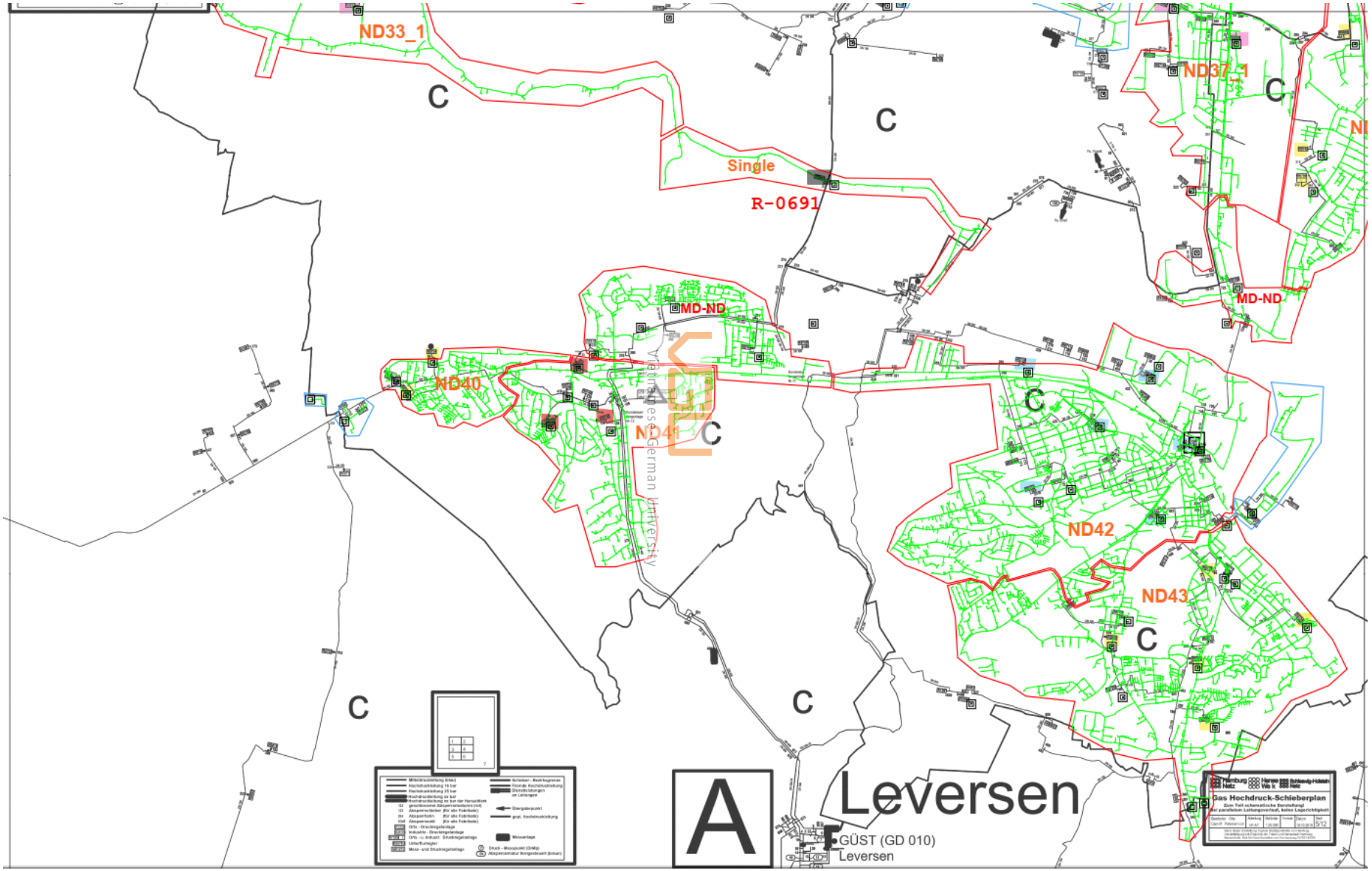
Upper-left section of the low-pressure map



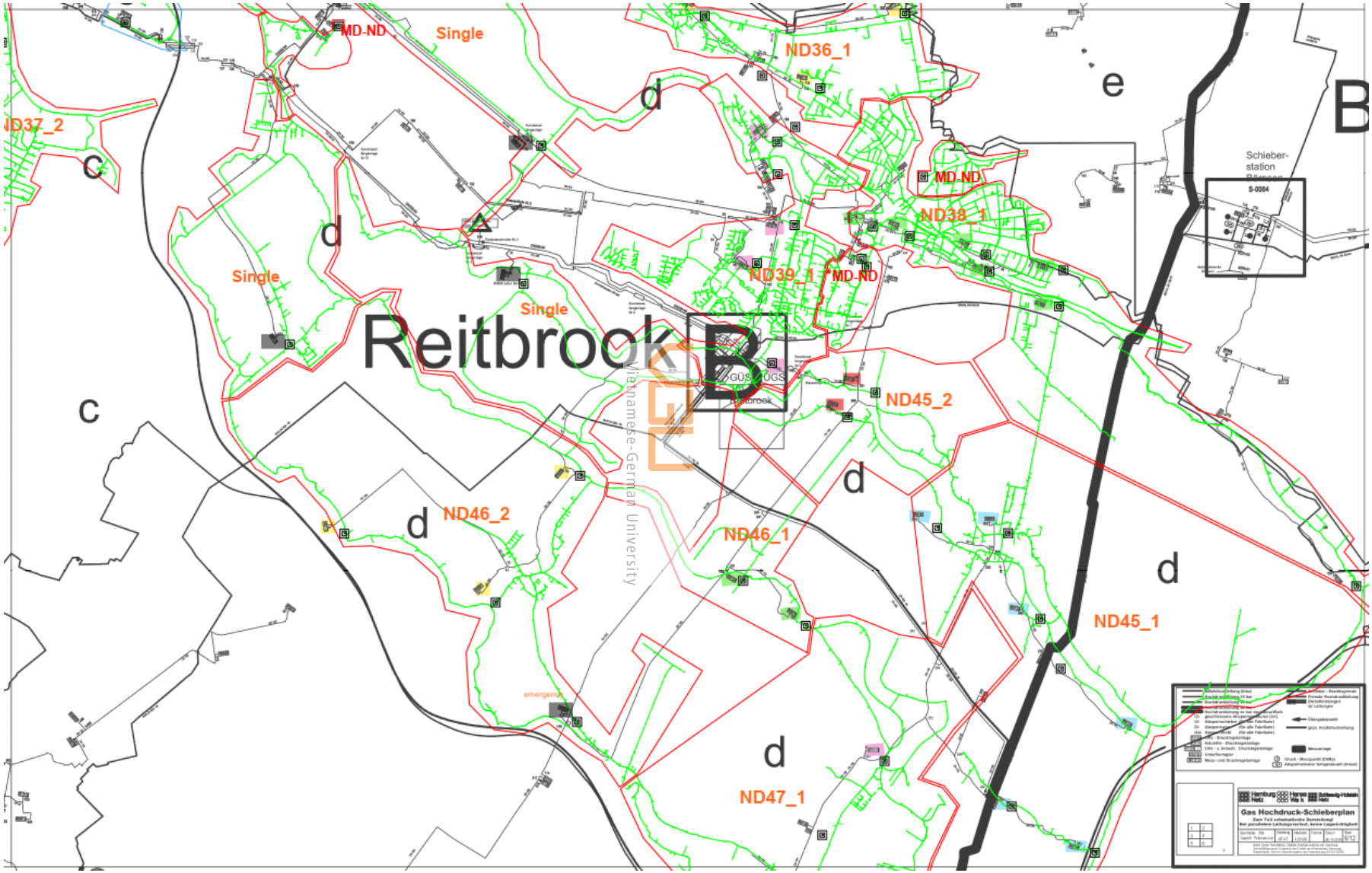
Middle-left section of the low-pressure map



Middle-right section of the low-pressure map



Lower-left section of the low-pressure map



Lower-right section of the low-pressure map

Appendix B: List of regulators assigned to the defined calorific value districts

Regulator	Exit node	District	Category	Sub-category
R-0691	K716231		single	
R-0073	K718334		single	
R-1015	K709394		single	
R-0115	K713783		single	
R-0089	K710229		single	
R-0059	K713936		single	
R-0044	K544801		single	
R-0046	K713858		single	
R-0460	K715317		isolated	
R-0714	5839		isolated	
R-0987	K705937	ND1_1	1	
R-0992	K714296	ND1_1		
R-1089	K718630	ND1_1		
R-1037	K705933	ND1_1		
R-1038	K714134	ND1_1		
R-1039	K705927	ND1_1		
R-1028	K714278	ND1_1		
R-0969	K714262	ND1_1		
R-0904	K714254	ND1_1	emergency	
R-0943	K708727	ND2_1	3	
R-1005	K712936	ND2_1		
R-0993	K709437	ND2_1		1
R-0955	K708685	ND2_1		
R-0963	K709404	ND2_2	2	
R-0964	K709401	ND2_2		
R-1081	K713660	ND3	2	
R-1080	6280	ND3		1
R-0984	K714122	ND3		
R-0988	K713643	ND3		
R-0971	K714132	ND3		
R-1077	K705907	ND4_1	0	
R-1045	K705913	ND4_1		
R-0937	K714092	ND4_1		
R-0905	K714247	ND4_1		
R-0911	K710120	ND4_1		
R-1088	K710117	ND4_1		
R-0982	6172	ND4_1		

R-0912	K714243	ND4_2	2	
R-0913	K714241	ND4_2		
R-1072	K710096	ND4_2		1
R-1049	K710083	ND4_2		
R-1030	K710085	ND4_2		
R-0906	K716606	ND4_2		
R-0914	K718577	ND4_2	emergency	
R-0985	K720788	ND5_1	2	
R-0907	K701391	ND5_1		
R-0918	K720774	ND5_1		
R-0909	K718588	ND5_1		
R-1276	K720767	ND5_1		
R-1035	K701787	ND5_1	emergency	
R-0390	K717845	ND6_1	2	
R-0391	K717851	ND6_1		
R-1307	K720413	ND6_1		
R-0392	K717836	ND6_1		
R-0434	K706119	ND7_1	3	
R-0514	K706764	ND7_1		
R-0496	K706106	ND7_1		
R-0365	K706113	ND7_1		
R-0367	K706746	ND7_1		
R-0427	K720389	ND7_1		
R-0938	K713635	ND8_1	1	
R-0939	K713392	ND8_1		
R-0991	K709900	ND8_1		
R-0957	K709345	ND8_1		
R-0916	K710069	ND9_1	0	2
R-1036	K710067	ND9_1		
R-0997	K714189	ND9_1		
R-0961	K710060	ND9_1		
R-0923	K701770	ND10_1	1	
R-0926	K720749	ND10_1		
R-0924	K701372	ND10_1		
R-1258	K718569	ND10_1		
R-1008	K701368	ND10_2	1	
R-1059	K720712	ND10_2		
R-0919	K701350	ND10_2		
R-1090	K718508	ND10_2		
R-0930	K720699	ND10_2		

R-1017	K718503	ND10_2		
R-1244	K718466	ND10_3	2	
R-0920	K714144	ND10_3		
R-0995	K701326	ND10_4	1	
R-0018	K718460	ND10_4		
R-0406	K719793	ND11_1	2	1
R-0521	K719802	ND11_1		
R-0544	K720066	ND11_1		
R-0525	K720046	ND11_1		
R-0409	K719786	ND11_1		
R-0402	5480	ND12_1	2	1
R-0401	K720075	ND12_1		
R-0398	K716009	ND12_1		
R-0501	K717811	ND12_1		
R-0383	K717761	ND12_1	emergency	
R-0411	K715929	ND12_1	emergency	
R-0385	K720303	ND13_1	1	
R-0387	K720282	ND13_1		
R-0479	K706638	ND13_1		
R-0372	K706670	ND13_1		
R-0437	5524	ND13_1	emergency	
R-0370	K706708	ND14_1	2	
R-0371	K706089	ND14_1		
R-0368	K706724	ND14_1	emergency	
R-0441	K709315	ND15_1	2	
R-0444	K709307	ND15_1		
R-1082	K713380	ND15_2	2	
R-0950	K709839	ND15_2		
R-0476	K705581	ND16	3	
R-1242	K705586	ND16		
R-0477	K705589	ND16		1
R-0599ND	K705512	ND16		
R-0515	K705505	ND16		
R-0465	K715103	ND19_1	0	
R-0524	K715092	ND19_1		
R-0469	K715059	ND19_1		1
R-0459	K715298	ND19_1		
R-0472	5559	ND19_1		

R-0471	K714773	ND19_1		
R-0458	K717348	ND20_1	2	
R-0470	K717346	ND20_1		
R-0453	K719989	ND20_1		
R-0462	K717366	ND20_2	3	
R-0420	K719777	ND20_2		
R-0440	K715919	ND21_1	2	
R-0480	K720011	ND21_1		
R-0414	K715905	ND21_1		
R-0425	K720270	ND22_1	3	
R-0421	K720209	ND22_1		
R-0454	K715855	ND22_2	1	
R-0450ND	K717636ND	ND22_2		
R-0445	K720200	ND22_2		
R-0486	K707170	ND23_1	3	
R-0436	K707207	ND23_1		
R-0433	K720613	ND23_1		
R-1268	6507	ND23_1	emergency	
R-0363	K708230	ND24_1	2	
R-0424	K708202	ND24_1		
R-0377	K708223	ND24_1		
R-0490	K708275	ND24_1		
R-1033	K709279	ND25_1	2	
R-1040	K709266	ND25_1		
R-0956	K713316	ND25_1		1
R-0953	K713313	ND25_1		
R-0025	K713293	ND25_1		
R-0718	K709251	ND25_2	2	
R-0845	K709705	ND25_2		
R-1076	K714031	ND26_1	2	
R-0944	K714040	ND26_1		1
R-1014	K714081	ND26_1		
R-0967ND	K716582ND	ND26_1	emergency	
R-1074	K713595	ND26_1	emergency	
R-0948	K716593	ND26_2	2	
R-0976	K714010	ND26_2		1
R-0921	K710029	ND26_2		

R-0975	K716558	ND26_2		
R-0973	K716561	ND26_2		
R-0027	K716531	ND27_1	2	
R-0021ND	5032	ND27_1		
R-0020	K710302	ND27_1		
R-1006	K710362	ND27_1		
R-0036	K718428	ND27_1	emergency	
R-0028	5040	ND27_2	2	
R-0050	K710011	ND27_2		
R-0031	K709994	ND27_2		
R-0051	K713952	ND28_1	1	
R-0053	K713580	ND28_1		
R-0127	K718404	ND30_1	1	
R-0122	K718703	ND30_1		
R-0131	K718341	ND31	1	
R-0118	K718354	ND31		
R-0060	K709634	ND32	3	
R -5999	K713179	ND32		
R-0047	5069	ND32		
R-0815	K705900	ND33_1	1	
R-0705	5828	ND33_1		
R-0833	K715005	ND33_1		
R-0686	5805	ND34	2	1
R-0760	K719918	ND34		
R-0775	K719741	ND34		
R-0684	K719951	ND34		
R-0664	K708101	ND35	2	
R-1256	K708526	ND35		
R-0121	K721005	ND36_1	1	
R-1273	K702301	ND36_1		
R-0074	K702148	ND36_1		
R-0130	K718693	ND36_1	emergency	
R-0666	K708093	ND37_1	2	
R-0695	K708484	ND37_1		
R-0696	K709121	ND37_2	2	
R-0745	K709107	ND37_2		1

R-0700ND	K709097	ND37_2		
R-0081	K702129	ND38_1	2	
R-0123	K702286	ND38_1		
R-0110	K702656	ND38_1		1
R-0086	K702658	ND38_1		
R-0084	K702831	ND38_1		
R-0085	5116	ND38_1		
R-0078	K701624	ND39_1	0	
R-0075	K701605	ND39_1		
R-0087ND	K701497-A	ND39_1		
R-0077	K701643	ND39_1		
R-0755ND	K715045-A	ND40	1	
R-0754	K715048	ND40		
R-0751	K715442	ND41	0	
R-0748	K719697	ND41		
R-0769	K715436	ND41		
R-0739	K706523	ND42	0	
R-0737	K706987	ND42		
R-0741	K706974	ND42		
R-0709	K707961	ND42		
R-0732	5860	ND42		
R-0713	K707951	ND42		
R-0720	K707911	ND43	2	
R-0724	K709080	ND43		
R-0805	K706910	ND43		
R-0725	K707829	ND43		
R-0727	K707841	ND43		
R-0101	K702231	ND45_1	1	
R-0093	K702634	ND45_1		
R-0088	K702613	ND45_1		
R-0138	K702804	ND45_1		
R-0120	K702815	ND45_1		
R-0124	K703223	ND45_1		
R-0129	K702079	ND45_2	0	
R-0094	K702056	ND45_2		
R-0099	5131	ND46_2	1	
R-0113	K716364	ND46_2		
R-0091	5122	ND46_2		
R-0095	K718262	ND46_2	emergency	

R-0128	K701437	ND46_1	1	
R-0076	K701431	ND46_1		
R-0114	K702048	ND47_1	1	
R-0111	K702031	ND47_1		
R-0422	K717672	MD1	2	
R-1286	K717669	MD1		
R-0133	K709920	MD3	1	
R-0119	K710239	MD3		
R-0075MD	K701605MD	MD4	0	
R-0078MD	K701623	MD4		
R-0081MD	K702129MD	MD4		
R-1329	K2076	MD5	2	
R-0665	K708080	MD5		
R-1324	K2063	MD6	0	
R-0736	K716224	MD6		