Modelling the impact of the energy transition on gas distribution networks in Germany

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Abstract:

The energy transition is leading to profound changes in all parts of the energy system, but the reduction of fossil fuels in the heating sector is a major challenge for the energy sector. The changing heat-generating structure also affects its supply infrastructures. The impact on the existing electricity infrastructure is evident and subject to a lot of research, but gas distribution networks are not considered in most studies. The ongoing defossilization brings the need to assess the impact on gas distribution networks. The assumption of gas as a bridge technology might lead to potential lock-ins or sunk costs. The central question reads: how will gas distribution networks change by 2050 as we move toward a greenhouse gas neutral energy system?

This question is answered by using a model network analysis called DINO to compute the infrastructure development and associated costs for existing greenhouse gas-neutral scenarios from present day until year 2050. The supply task and the necessary network elements with their physical parameters are included in the model, and the cost-optimal gas distribution network infrastructure is calculated for each county in Germany.

In short, the infrastructure analysis shows a declining need for gas distribution networks for all given GHG-neutral scenarios. In all-electric scenarios, the network length of the required grid infrastructure decreases to zero by 2050. Even in moderate scenarios with high shares of synthetic gas in the heating system, less gas distribution infrastructure is needed. The results of the research presented in this paper can be used to support the necessary measures to ensure a development of gas distribution networks that support greenhouse gas neutrality.

Keywords: energy transition, heating transition, model network analysis, gas distribution grid, synthetic gas, defossilization

1. Introduction

The effort to reduce global greenhouse gas emissions has led to both national and international commitments: for example, the Paris Agreement [1] provided an important boost to the cause in 2015. In Germany, the government has set ambitious goals with the recent defossilization [2]. The result is a fundamental shift to renewable, carbon dioxide (CO_2)-neutral energies within global energy supply. The phase-out of fossil fuels will present a major challenge over the next few decades, but the decision to exit coal has already been taken in Germany [3]. However, the acceptance of gas as a bridging technology is currently being questioned, as there is a risk that further investments in the gas sector will jeopardize the German government's climate targets defined by the Paris Agreement [4].

A key sector for reducing greenhouse gas emissions is the heating sector. Despite the progress of renewable energies (i.e. in power generation), there have been few reductions in CO_2 emissions: this is in part due to the fact that the heating sector accounts for more than 50% of final energy demand, and renewable energy has a share of only 14% of heat consumption. Because gas plays a key role in the provision of decentralized heat for buildings, reducing the dependency of this sector on fossil fuels can contribute significantly to the reduction of overall emissions [5], [6].

Natural gas is a fossil fuel that is used in a wide range of applications. Industrial customers use natural gas to generate energy for process heat processes or as a material in the basic chemical industry. Power and heating plants use natural gas to generate electricity and district heating, and the residential and trade/commercial services (TCS) customer groups mainly use natural gas to generate space heating and hot water [7]. The share of the customer groups private households and TCS in the total gas consumption was about 41.5% in 2019 [7]. Currently, 48% of the residential sector in Germany is heated by natural gas technologies [8].

Nationwide, natural gas is distributed by long-distance gas pipeline companies (FNB) in Germany. Local distribution to households and the TCS sector is made by gas distribution network companies (VNB) [9]. Overall, around 80.5% of gas is transported to end customers via the distribution networks, which supply around 10.5 million connections and around 14.24 million metering points across Germany [10]. However, the extent to which the gas distribution network infrastructure is developed varies from region to region. The importance of natural gas in heat supply thus differs in Germany due to the historical growth of gas supply and access to domestic gas fields (e.g. in Lower Saxony) [8].

In order to minimize the amount of greenhouse gases produced, there is a need to reduce the importance of fossil fuels. Increased efficiency will aid in this goal because a better efficiency will lead to less heat demand. This increase in efficiency will be seen through the renovation in the building sector and the replacement of heating systems, leading to an expected decrease in the consumption of natural gas. Various studies predict savings of 43-65 % by 2050 for space heating and hot water. In the technology mix for heat supply, these studies include renewable technologies such as solar thermal, district heating, biomass, and electricity-based technologies (such as heat pumps). Natural gas is replaced by synthetic gas in some greenhouse gas (GHG)-neutral scenarios, and the potential for the use of renewable sources for heat supply varies regionally [11]–[13].

The necessity of the heat turnaround as part of the energy turnaround is obvious. However, scientists and politicians do not yet have a fixed supply scenario for climate-neutral heat supply. The infrastructure must also be considered in order to make recommendations for a cost-optimized and economical heat supply. Today's investments come with potential for lock-ins or sunk costs. The structural changes within the energy supply infrastructure are affected by pathway towards greenhouse gas neutrality. Thus, we want to investigate the development of distribution networks by 2050 under greenhouse gas-neutral scenarios.

This paper is therefore structured in the following way: Section 2 provides an overview about current studies on gas distribution networks. Based on these studies, we provide our modelling approach. In Section 3, the approach of modelling gas distribution grid with a model network analysis (MNA) and the tool DINO is described in detail. Section 3 also includes the method and the used data set. The results are then presented in Section 4. Discussion of the results and assumptions are discussed in Section 5, and Section 6 gives a conclusion and points for further research.

2. Status of gas distribution infrastructure

The impact of the energy transition on existing infrastructure is the subject of many studies. Nevertheless, most studies focus on the impact in electricity infrastructure. For example, Bürger [14] shows that (electricity) distribution grids are essential for the energy transition. Agora Verkehrswende et al. [15] focus on electricity distribution grids and the effects of the electrification of mobility. Döring et al. [16] focus on the impact of the energy transition on grid bottlenecks reduction options in the electricity sector. Other studies investigate and model the link between the electricity and gas sector like Robinius et al. [17], Henni et al [18] or Al-Obaidi et al. [19]. Often, only the electricity grid is explicitly mentioned in these studies, but the use of gas infrastructure is described as beneficial.

In the case that energy system studies include the gas sector, they do not specifically address the grids. When energy transmission networks are included, this usually only refers to electricity transmission networks. The gas grid infrastructure is generally considered to play a relevant role in the transport of climate-neutral gases or as interface between gas and electricity sector [20]–[24]. A more detailed analysis of the gas infrastructure is often only carried out for a conversion of the transport networks to hydrogen [25]–[27].

Gas distribution networks are rarely investigated or not even considered in most studies. However, there are individual exceptions. Studies like Blanco et al. [28] have a systemic view on the integration of synthetic methane. They identify drivers and barriers for the integration of synthetic methane. One crucial part is the role of the gas grid: In the study, they state that a more detailed regional analysis is necessary.

Sadler et al. [29] focus on the conversion of distribution grids to hydrogen for the north of England. However, the assumptions are not aligned with the necessary development in the entire energy system. They indicate that conversion would be possible if hydrogen is an option. A more detailed look at the

German gas distribution networks is provided by Wachsmuth et al. [30] and frontier economics et al [31], and they try to specify the impact of the energy transition on gas distribution networks based on projections and case studies. Neither study shows modelling of all distribution networks in Germany.

The current state of studies shows that there are large uncertainties regarding the effect of energy transition on gas distribution networks. Energy system studies indicate a probable reduced relevance of the gas distribution network in greenhouse gas-neutral system. The required measures in the gas sector are unclear, and the scope of infrastructure depends on which transition scenario is implemented.

This leads to the following questions: How will gas distribution networks change by 2050? What is the transition pathway in a specific scenario? What are the transition costs in the gas distribution networks?

There are two suitable approaches to answer these questions. The approaches to figure out the infrastructure and associated costs are the MNA and the reference network analysis [32], [33]. Both approaches are used to model electricity, gas, and telecommunications networks under natural monopolies [9], [34]. A unit quantity structure (UQS) and the associated network costs are determined for a given supply task [34].

Reference network analysis requires detailed input data at high spatial resolution. For the calculation of the reference networks, the data of the distribution network operators would be necessary. They are very accurate representations of the topology of gas distribution networks. The spatial and technical conditions are represented very precise [35]. However, the data of the distribution system operators are not freely available for all distribution system operators, and the published data are not always homogeneous and available in the same form. The advantages of reference network analysis become evident in specific single-case studies [34]. The model network analysis describes the supply task with a minimum of input variables and is proven for the modelling of electricity distribution grids. The assumptions for the simplification are in principle that all connection points are homogeneous in their consumption and, and that network assets are uniformly distributed over the network area [36]. Basically, the MNA does not model a real network, since no individual case-specific boundary conditions for the supply areas are considered. However, this makes the MNA much more suitable for efficiently modelling the inventory of an entire country [33]. Furthermore, it is well suited for the open-source approach, since it is possible to use freely available, public data. This also has the advantage that, compared to studies with closed-access data and black-box models, a better reproducibility of the results is possible.

In this paper, the MNA is chosen because of the small amount of required input data for an accurate determination of the UQS for all of Germany. In addition, the simple model approach makes it very easy to determine the drivers of network development. Our approach is described in Section 3.

Another important input in order to answer the questions proposed in this paper are the results of current energy system studies. We want to illustrate the spectrum of potential development in gas distribution networks. Two extrema of possible pathways are observed in the energy system studies. On one side, we consider all-electric (EL) scenarios. This is characterized by a complete gas phase-out in the heating sector, and it is represented by the scenario “Klimaneutral 2050” (climate neutral) of Prognos et al. [23].

On the other side are scenarios with high shares of synthetic gas / methane in the heating sector. The synthetic gas / methane (SG) scenarios are represented by the scenario "Technologiemix 95" (technology mix) by Hecking et al. [22]. Since there is no current energy system study on the use of hydrogen in heat, we cannot rely on a pure hydrogen scenario [11].

3. Modelling changes of decentral gas distribution grids

The consideration of the development of the gas distribution network infrastructure is carried out in four steps as described in figure 1. First, the input data is prepared. The basis data consists of the gas consumption in the sectors supplied by the gas distribution networks (households, TCS and industry). Two scenarios of trends from energy system studies are used. The gas demand of the sectors on the level of whole Germany is in the second step allocated in terms of quantity and time at the NUTS3 level (counties). For this purpose, methods from the DemandRegio project are used [37].

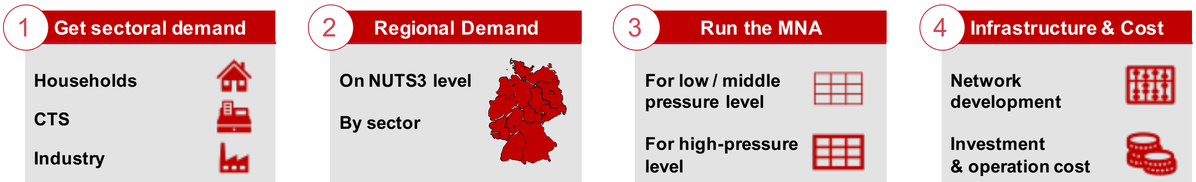

Figure 1: The four steps of our approach

The third step is the MNA itself. We created the gas Distribution grId modelliNg tOol (DINO) to compute the MNA. The data prepared in step one is used to calculate the optimal gas distribution network infrastructure. The result is a UQS for each scenario and scenario year. Furthermore, the associated costs of the gas distribution network in Germany are assessed.

The fourth step is the comparison of the UQS and cost. The comparison allows a predication of the infrastructure development associated with the scenarios. The result is a determination of the amount of grid expansion, or decommissioning, and the associated costs.

3.1 Model network analysis with DINO

The effects of the changing gas demand in the distribution grids can be analysed based on the model network analysis (see figure 2). The MNA is a very abstract analysis of the supply task of a network operator where the minimum necessary quantity structure of operating units can be determined given the supply task using only a few input parameters. Based on the number of operating units, it is possible to determine infrastructure cost. The comparison of different points in time also allows for the derivation the network development and associated costs [34].

The MNA is based on five key assumptions. (1) The MNA represents a greenfield approach, which is an approach which lacks constraints known to previous works. (2) The analysis assumes a homogeneous supply structure within the considered area. This includes a homogeneous distribution of connection points, pipeline routes, and the locations of other equipment. (3) The supply task is significantly simplified. There are no analyses of flow situations in the gas distribution network. The supply task is estimated based on demand quantities and load peaks. (4) Therefore, the real network topology is neglected and only represented in a simplified way. (5) Insofar, the result of the MNA represents an optimal quantity structure of operating units for ensuring the supply task [34].

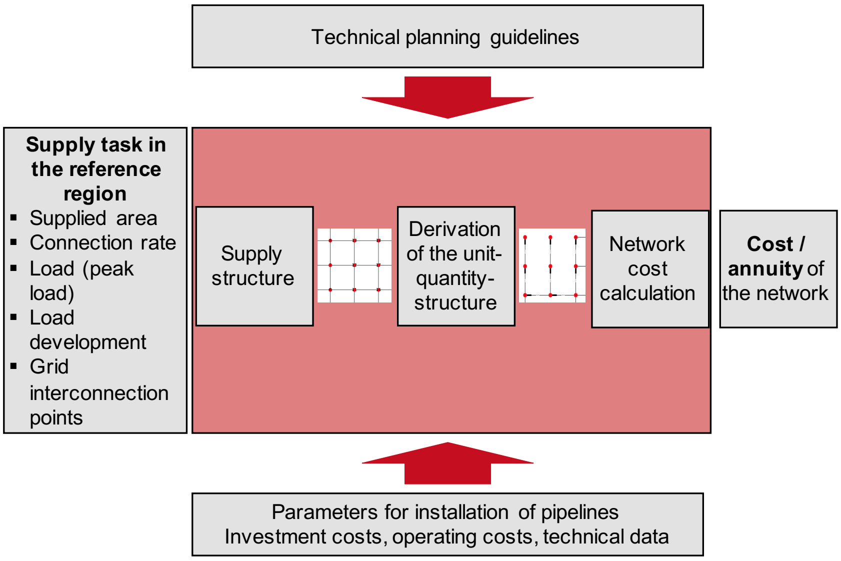

Figure 2: The principle of the model network analysis according to Fritz [36] and Consentec GmbH et al. [34]

The input variables for DINO can be divided into two groups [20], [34]. First are the input parameters that are relevant for the calculation of the UQS. To calculate the optimal network structure, the number of connection points, the supplied network area, the peak load, and a simultaneity factor of the gas withdrawal per connection point are required. The number of connection points corresponds to the number of exit points for the withdrawal of gas from the distribution network by the different end customer types. These are the main design-relevant input factors. The network area is the total area over which the connections are distributed, and it is decisive for the density of the connections. The peak load influences the dimensioning of the line diameters, and the simultaneity factor is a statistically determined value for estimating the simultaneous maximum load of all exit points at a pressure level [34]. The coincidence factor for distribution and consumption lines is usually assumed within the range of 0.4 and 0.9 [9].

Second come the parameters for determining the network costs. The UQS forms the basis for the net costs. The calculation is based on data about the costs of the pipes, the gas pressure measuring and regulating stations (GPRM) and the consumer connections. The costs for the various pipeline diameters are made up of direct pipe construction and specific installation costs, and the installation costs depend on the ground conditions [9], [34], [38].

The calculation of the gas distribution network is executed in two stages. The first step is to determine the UQS for the low and medium pressure stages. This covers the network levels where households and the majority of the TCS Sector are connected. In the second step, the high-pressure level is calculated. In this step, the industrial consumption in the distribution networks is taken into account, and the GPRMs from step one come in as cross points between the network layers and customers in the high-pressure level.

Three main physical influencing factors are considered in DINO. These are the pressure losses during gas withdrawal at the exit points, pressure losses due to friction during transport in the pipeline, and Kirchhoff's circuit laws.

In utility engineering, the Darcy-Weisbach equation is used to calculate the pressure loss (Δp_{v}) of a pipe. The prerequisite is that the flow within a pipe is stationary and turbulent [39]. A stationary centrifugal condition is given by assuming homogeneous time load distribution. The pressure loss of a fluid over the length (l) of a pipe results from friction between the fluid and the pipe wall (described by the pipe roughness λ). Due to known pipe diameters (d) in the gas supply, the pressure loss can be considered simplified with the following equation in DINO. In addition, the density of the fluid (δ) and the flow rate (V^2) are included in the simplified equation [40].

$$\Delta p_{\mathrm{v}} = \lambda * \frac{l}{d^5} * \frac{8 * \delta}{\pi^2} * V^2$$

Kirchhoff's rules were originally used for the network calculation of electrical networks. However, the mesh and node approach can be adapted to gas volume flows [40]. The nodal law states that the sum of all inflows and outflows ($\dot{V}_k$) in a node is zero.

$$\sum_{k=1}^{j} \dot{V}_k = 0$$

$$j \text{ } as \text{ } Number \text{ } of \text{ } edges \text{ } to \text{ } or \text{ } from \text{ } the \text{ } node$$

The mesh law states that the sum of all pressure losses in a mesh or loop is zero. The mesh law can be neglected in this case due to the tree approach of DINO [40].

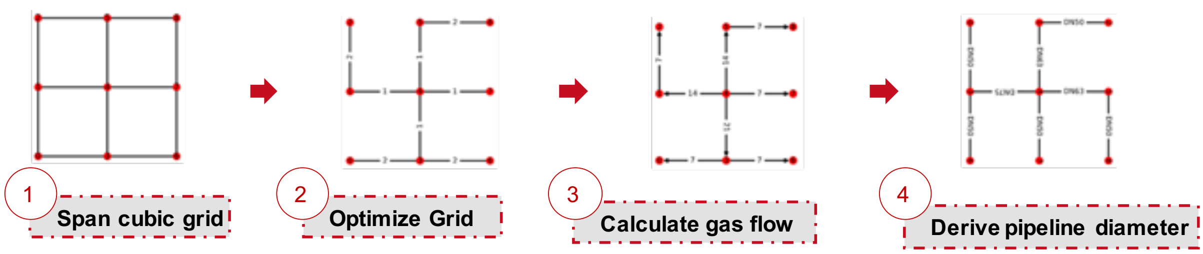

Figure 3: Steps of the MNA to derive the optimal gas distribution grid.

The procedure of DINO to determine the UQS is done in four steps shown in figure 3. First, a cubic lattice is spanned, and the connection points are evenly distributed over the surface, which corresponds to the supply area within a region. In the second step, all points are connected by means of a minimum spanning tree. A ray network is spanned starting from a source node. In the third step, the gas flow on each edge is calculated, and the pressure drop is included as a constraint to ensure the supply by the simplified Darcy-Weisbach equation. This is done starting from the end points of the rays back to the source. This ensures that all connection points are supplied with sufficient gas and pressure. Then, the required pipeline diameters are assigned on the basis of the determined volume flows. The necessary GPRM are finally calculated based on the network and used pipeline diameters.

The iterative procedure starting from the end points of the branches allows the calculation of the required diameter for each connection. The pressure at the final node of a branch must be greater or equal than 1.0133 bar. The length between two nodes is known. Thus, it is possible to determine the pressure at previous nodes. The flow at a given segment is calculated with the following formula, where the available standard diameters for distribution networks are known (d). On this basis, it is possible to iterate through the list of diameters. The flow must be greater than on the previous edge. Hence, the smallest diameter to which this applies is selected.

$$Flow_{ij} = \sqrt[2]{\frac{d_{ij}^5 * T_{norm} * \pi^2 * \left(p_i^2 - p_j^2\right) * 3600^2 * \frac{10^5}{16}}{\lambda * l * \delta * K_m * T * p_{norm}}}$$

$$s.t. Flow_{ij} \geq Flow_{i,j-1}$$

Two sets of nodes are formed to determine the GPRM. GPRM are to be installed only at nodes located in both sets. The first sets include all nodes that are connected to the largest pipeline diameter available. The second set of nodes have a connection to smaller diameters. The intersection of both sets returns nodes that are assumed to be locations of the GPRMs.

$$DN_{larger} = \{nodes \ \in DN = DN_{max}\}$$

$$DN_{smaller} = \{nodes \ \in DN < DN_{max}\}$$

$$GPRM_{\text{Total}} = DN_{larger} \cap DN_{smaller}$$

The UQS consists of pipelines differentiated by diameter and the GPRMs at each network level. The UQS is used in the next step to determine the cost of gas network infrastructure. The total network cost (C_{Total}) consist of the pipeline-related cost ($C_{\text{Pipelines}}$), the connection point cost ($C_{\text{Conection}}$), and the GPRM cost (C_{GPRM}). The total cost is the sum of these three components.

$$C_{\text{Total}} = \sum C_{\text{Pipelines}} + C_{\text{Connection}} + C_{\text{GPRM}}$$

The pipeline-related costs depend direct on the pipe construction cost (C_{Pipetype_i} in EUR/meter) for the necessary diameter (i) and lengths (l in meters) of the respective pipeline. Assumed installation costs are included on a pro-rata basis depending on ground conditions. It is distinguished between topsoil surface (IC_{T_i}), concrete surface (IC_{C_i}) and asphalt surface (IC_{A_i}) and their respective shares (p_{T} (65%), p_{C} (15%) and p_{A} (20%)). A percentage (p_{CS}) of the pipeline-related costs is assumed for the other costs of the construction site equipment.

$$C_{\text{Pipelines}} = \sum_{i=0}^{n} \left(\left(C_{\text{Piptype}_i} + IC_{\text{T}_i} * \ p_{\text{T}} + IC_{\text{C}_i} * \ p_{\text{C}} + IC_{\text{A}_i} * \ p_{\text{A}} \right) * l_i \right) * \ (1 + p_{\text{CS}})$$

The connection costs result from the product of the costs per connection ($C_{\text{Connectiontype}}$) and the number of connections on the pressure level ($A_{\text{PressureLevel}}$).

$$C_{\text{Connection}} = C_{\text{Connectiontype}} * A_{\text{PressureLevel}}$$

The costs of the GPRM are also determined per pressure level (C_{GPRM}). These are the product of the cost per type of GPRM and the number of required GPRMs ($AGPRM_{\text{PressureLevel}}$).

$$C_{\text{GPRM}} = C_{\text{GPRM}} * AGPRM_{\text{PressureLevel}}$$

The annual network costs are presented as an annuity for comparability and consists of capital expenditure (CAPEX) and operational expenditure (OPEX). This allows a more realistic comparison of the network costs determined by the greenfield approach. Component-specific lifetime (n_T in years) are considered. OPEX are also included for each component as an annual percentage of the investment costs ($OPEX_T$). The annuity for the gas distribution infrastructure is the sum of CAPEX and OPEX over all regions (R) in Germany.

$$Annuity = \sum CAPEX_R + OPEX_R$$

The UQS as well as the total network cost and annuity are calculated for each pressure level separately. The sum of the calculation of the low- and medium-pressure level on the one hand and the high-pressure level on the other hand result in the UQS and the costs for the entire gas distribution network infrastructure.

The development of the infrastructure is derived from the comparison of the results for the considered reference years. Infrastructure expansion is a given in the case of a larger UQS (such as a longer distribution grid). Investments in the grid can be identified directly from increased grid costs respectively a higher annuity. Dismantling of infrastructure exists in the case of a smaller UQS, and costs associated with decommissioning require further analysis of the difference between the UQS in the scenario years. The information in table 3 in the following section is used to calculate the estimated decommissioning costs. Through comparison of the results for the different scenario years, the impact of the heat transition on the gas distribution networks can be determined and analysed.

3.2 Model inputs

Two types of inputs are used to determine the development of gas distribution networks. One part is technical and is used for the calculation of the UQS. This includes data on the development of gas consumption in the utilized scenarios. The other part is the basis for the economic analyses.

Table 1 lists the general technical physical input parameters. These parameters are used in the calculation of the gas flow in the edges.

Parameter	description	Value	unit
Lambda	Pipe roughness	0.026	[cm]
K_m	Compressibility Factor	0.91	
Rho_{norm}	Density	0.783	[kg/m3]
P_{norm}	Pressure at end node	1.01325	Bar
T_1	Temperature	285	K
T_{norm}	Temperature	273	K

Table 1: Technical and physical input parameters according to Cerbe et al. [9], Homann et al. [39] Mischner et al.[41], and DVGW [42]

Standard diameters used in gas distribution networks are used for the network modelling. For the first loop in the low and middle pressure level, DN32 to DN225 are used. In the second loop for the high-pressure level of the distribution grid pipelines, up to diameter DN630 are used. For further data, see appendix.

The costs for the infrastructure elements, as well as the costs for the connections and GPRM are shown in Table 2. The costs for the pipelines are diameter specific. For the calculation of the annual operating costs, the applied share of CAPEX is listed. In addition, the different lifetimes of the infrastructural elements are considered. The last two parameters are necessary to determine the annuities (see previous section).

	Cost [€/unit]	Share of CAPEX [%/a]	Lifetime [a]
Pipeline	Depending on diameter	0.8	45
Connection	2,500	0.8	25
GPRM	14,000	5.8	25

Table 2: Cost parameters for gas distribution grid elements according to frontier economics et al. [31], Cerbe et al. [9], Homann et al. [39] and FNB Gas [43]

Cost data from frontier economics et al. [31] is shown in table 3 and used for the costs of decommissioning network elements. In addition, an extension of this data by Wachsmuth et al. [30] is used, which allows one to take current uncertainties of decommissioning costs into account. As a result, we can show the range of decommissioning costs for given scenarios. We consider three different decommissioning options. The most expensive option is deconstruction: for deconstruction, all pipeline elements must be removed from the ground. The cheapest option is sealing, which can be used for a large part of the pipelines. Since small diameters are mainly used in gas distribution networks, it is possible that almost all pipelines are affected by this measure. Thus, the share of the other measures decreases in the low-cost variant. In addition, it is taken into account that for the third measure, the filling and sealing, the costs can also be lower in the low-cost assumption [30].

Decommissioning Type	High share	High-cost assumption [€/km or element)	Low share	Low-cost assumption [€/km or €/element]
Deconstruction	5.0%	280.000	0.5%	280.000
Filling and sealing	30.0%	200.000	3.0%	70.000
Sealing	65.0%	20.000	96.5%	20.000
GPRM high pressure		75.000		75.000
GPRM low and middle pressure		10.000		10.000

Table 3: Decomissioning parameters for the high cost and low cost case according to frontier economics et al. [31] and Wachsmuth et al. [30]

Further inputs are the demand development in the two scenarios used in this paper. The demand development is a key input for the grid development. In both scenarios, the synthetic gas scenario and the all-electric scenario, a declining gas demand is shown by the studies. As described above, we used the data from the DemandRegio project to allocate the demand on NUTS3 level (European classification of territorial communities on the district level) in Germany. We used the disaggregator data for 2017 as the basis for the allocation for all sectors. Since the GHD and PH sectors are combined in both studies, we used the DR data for 2017 to derive the ratio of the two sectors. For the base year and all scenario years, it is assumed that the distribution between NUTS3 regions and the two sectors does not change.

Industrial gas consumption is regionalized in a slightly different way, because which part of the demand must be allocated to the gas distribution networks first must be determined. Based on Wachsmuth et al. [30], approximately 65% of the industrial gas demand is supplied directly via the transportation grid. Thus, 35% of industrial demand is supplied from the gas distribution network. This number is also derived from public data by ENTSOG [44] and AGEB [7]. We took the direct consumer supply in the transportation grid and subtracted all demands by other sectors (e.g., energy industry). Assuming that the remaining part is industry, we can derive the share by dividing this figure by the total German industrial gas demand.

Industry-specific profiles are used for the regionalization of the gas consumption. Industries with high consumption are assigned directly to the gas transmission network. This applies to the steel, metals, glass, and ceramics sectors as well as the entire basic chemicals industry. For the regional consumption, CO_2-emissions and employee numbers serve as proxies. The demand across Germany for all sectors can be seen in figure 4.

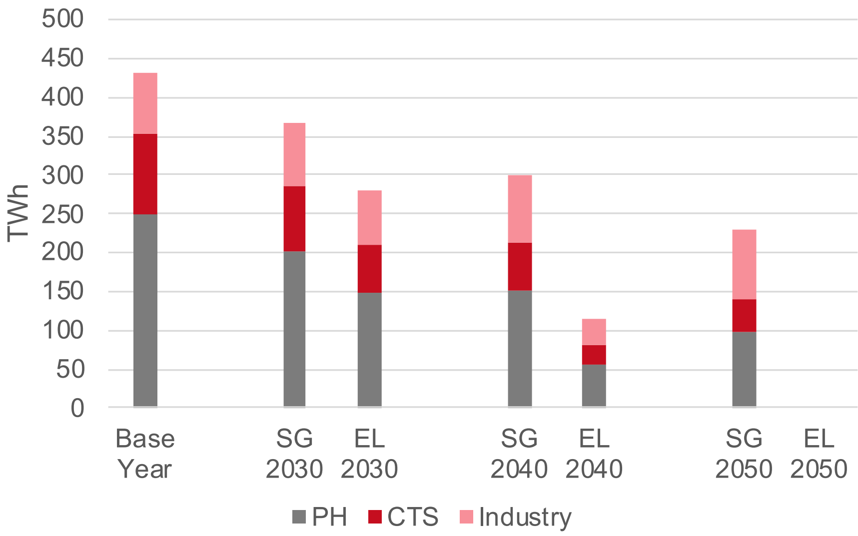

Figure 4: Demand development in Germany by sector and scenario

4. Results

In the first step, the results for the base year are compared with data from publicly available sources. The comparison is performed on a national level as well as for individual NUTS3 regions. A comparison for all regions is not possible due to missing data. Values from distribution system operators for individual cities and counties were only available for 27 regions, due to limited data availability and because the boundaries of the service areas do not correspond to the NUTS3 regions. The comparison shows that the modelled network lengths and amount of GPRM correspond to reality.

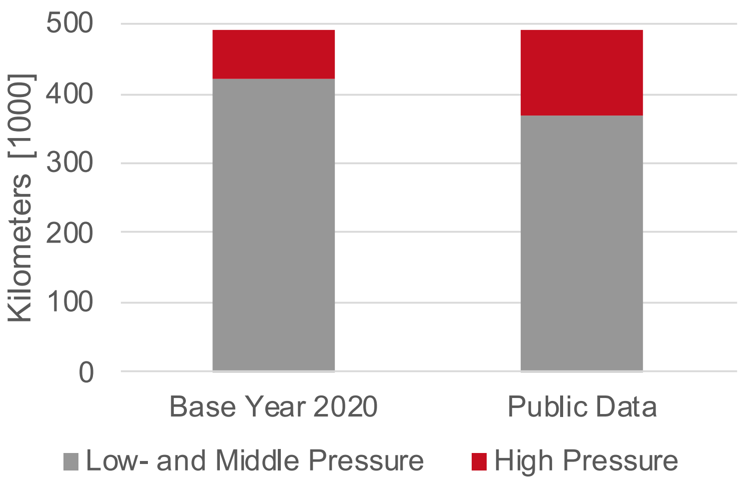

Figure 5: Comparison of modelled results and official grid length for whole Germany in the base year.

The total length of all distribution networks in Germany is around 480.000 – 493.000 kilometres [31], [45]. The output of DINO shows around 490.000 kilometres for the base year, but the underestimation (see figure 5) of the high-pressure stage can be explained by the modelling approach. For one thing, the separation between the pressure levels is not as sharp as in our model. Second, we have only assigned the industry to the high-pressure stage. Other consumers are also connected here. Furthermore, DINO shows 48.000 GPRM in Germany, which is in line with the data on GPRM in

Germany. Other publications indicate a value between 40.000 and 53.000. The ratio between the pressure levels also corresponds to reality [30], [31], [46].

The second part of the comparison shows that for most of the NUTS3 regions, the network lengths are well represented (see figure 6). The average deviation is 87 kilometres, and the mean absolute percentage deviation is 25.5%. However, this is caused by a few outliers. The absolute median deviation is only 19 kilometres, and the relative median percentage deviation only 3.0%. The sample is also small due to the data situation with only 26 comparison regions. It seems that urban regions are slightly overestimated and rural region are underestimated. But, with only four rural regions, a closer look for validation of this hypothesis is not possible.

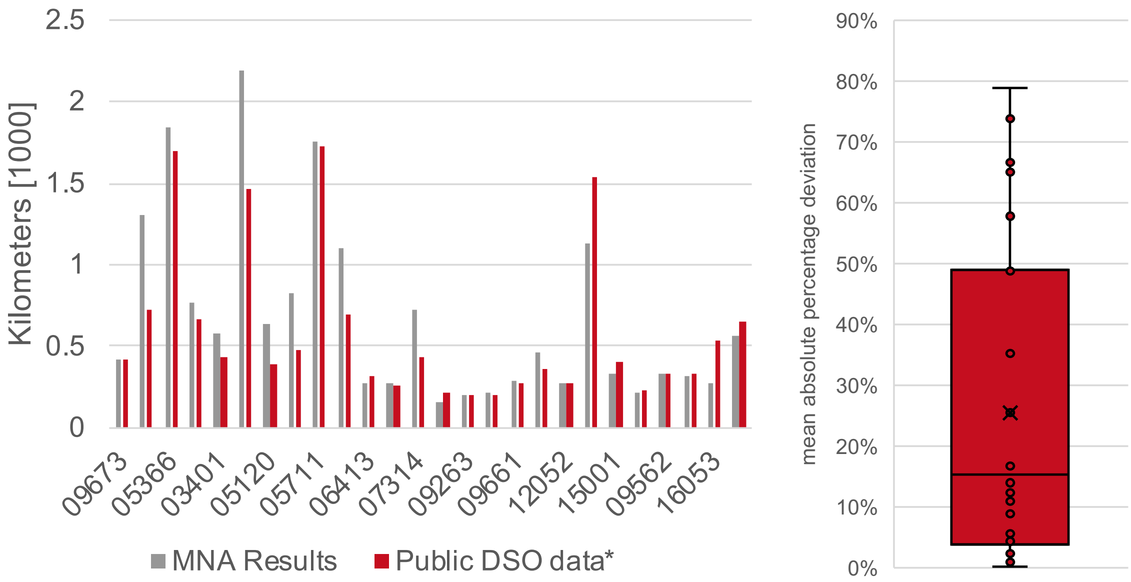

Figure 6: Comparison of modelled results and official grid length for regions that are supplied by only one gas distribution grid operator in the base year.

Furthermore, high deviations can be explained because the published data is not consistent. In some cases, they contain data including the connection lines to the consumers that are not modelled by DINO. This is e.g., the case in region 05711. House connection lines are included but without further specification if they are part of the sum or not. The error was significantly reduced by transferring the ratio of connection lines to total new lines from all other regions to 05711.Taking these facts into account, DINO shows that it is a very good representation of reality and can be used to answer the research questions. We obtain the following results and, the development of the distribution networks in Germany in the two scenarios are discussed in the following.

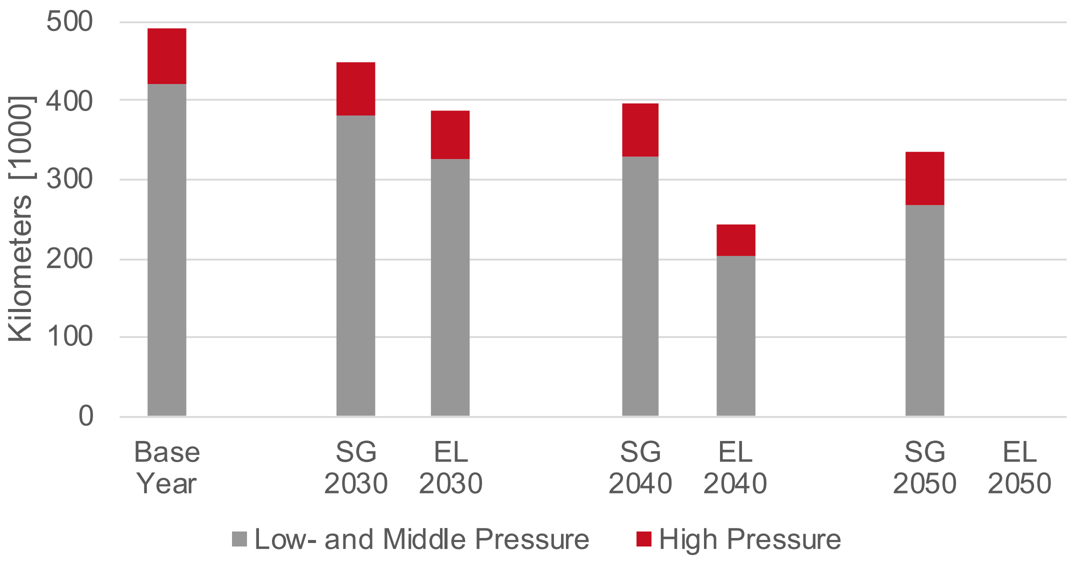

Figure 7: Development of the gas distribution grids in Germany by scenario and modelled year.

In both scenarios, a declining amount of network infrastructure is shown in figure 7. The reduction of the gas distribution networks starts from now on. In 2030 there is already a slight difference between the SG and the EL scenario. The gap is increasing until 2040, when the EL scenario has only half of the current network length. In 2050, the SG scenario requires one third less infrastructure compared to today's distribution grid. In the EL scenario, there is a reduction in network length to zero in 2050.

The reduction of the gas distribution grid is mainly observed in the low and middle pressure level. The high-pressure level is almost constant. This can be explained in the SG scenario by the increase in demand from connected industrial consumers. The decline in the EL scenario is initially less drastic. There is no network reduction in the high-pressure level until the phase-out of gas towards the end of the observation period. In both scenarios, the main driver for grid reduction is the declining demand for space heating and warm water by households and CTS. In all scenarios, GPRMs decline along with the networks.

The decommissioning of the gas distribution networks implies costs in both scenarios. In both scenarios, the main cost driver is the decommissioning of pipeline segments. The GPRM contribute only a small amount to the costs, and they are lower in the SG scenario due to the lower infrastructure reduction pathway. The partial decommissioning in the SG scenario is associated with costs of 4.2 to 14.2 billion euros. The complete decommissioning of the distribution grids in the EL scenario shows costs between 12.2 and 43.7 billion euros. In the following, it is assumed that savings must start today (in 2021) and the amount must be available in 2050. An annual financing volume can be determined for both scenarios, given this assumption. The annual financing in the SG amounts to a sum between 180 and 640 million euros. The annual financing amount in the EL scenario is between 540 and 1.950 million euros.

The annuities of the operation and the financing of the decommissioning are combined to compare the two development paths. The annuities are based on the specific lifetime and cost parameters of the operating assets for the required infrastructure each year. For more detailed explanations, see section 3.1. The development is shown in figure 8. The main cost blocks depend on the scenario.

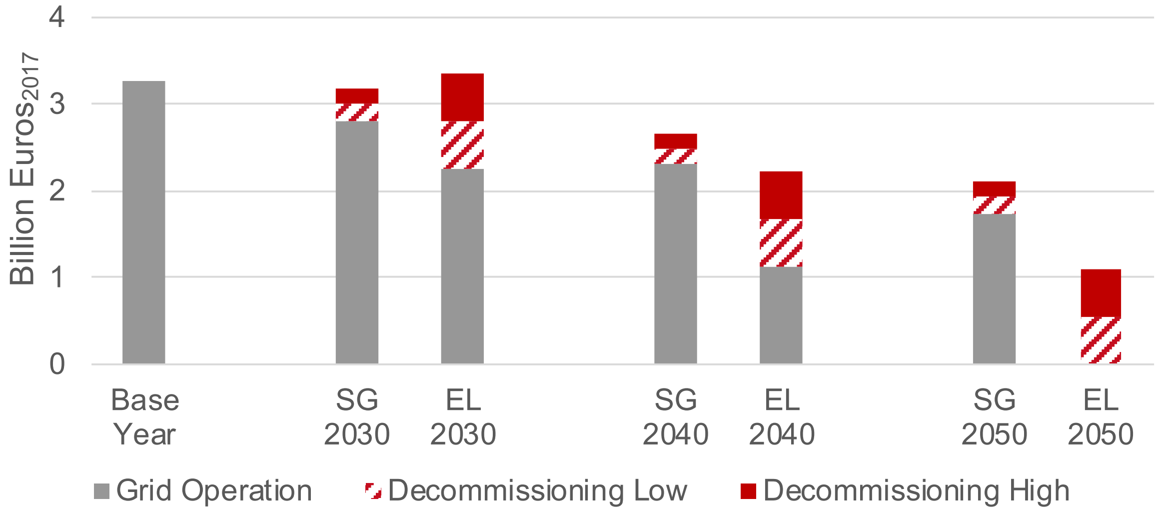

Figure 8: Development of the annuities for grid operation and decommissioning in Germany by scenario and modelled year.

Grid operation cost in the base year amount to 3.2 billion euros. They are declining in both scenarios due to decreasing infrastructure needs. Operating costs are the greatest cost block in the SG scenario in all modelled years. The grid operation cost in the SG scenario in 2050 are still 50% of today's grid operation cost. Up to 11 % of the total annual costs in 2050 in the SG scenario account for the decommissioning of grid elements. The costs in the EL scenario are dominated by decommissioning costs in the long term. From 2040 onwards, more than 50% of the annual costs are driven by the decommissioning of the gas distribution grid. Decommissioning costs are the only cost block in 2050. The amount depends only on the different applied cost factors.

The results show that there will be reductions in gas distribution networks in greenhouse gas neutral scenarios. The costs are significantly determined by the decommissioning measures in the long term, and costs may initially be higher in the EL scenario than in the SG scenario. However, in the long term, the costs in the gas distribution network are lower in the EL scenario. This is because from 2050 onwards, grid operation will no longer exist, and only one cost block will exist.

5. Discussion

A validation for the satus quo showed that real volumes can be approximated with the gas Distribution grId modelliNg tOol (DINO) by applying an MNA approach. In the case of a more detailed development in individual regions, the following aspects must be taken into account. It is necessary to have more accurate information about the existing gas network infrastructure. With this knowledge, it would be possible to subdivide a NUTS3 region into sub-regions [20], [34]. These can then be specifically considered regarding the input parameters (area, connected consumers, gas demand). Nevertheless, public data is not available in sufficient quality. The approach could rather be used for individual case studies.

DINO shows that the gas distribution grid development is primarily driven by overall development in the energy system. We show that the main driver of network reduction is the declining demand. This effect can be observed in the lower and middle pressure level. Household and CTS demand declines in each modelled year under both scenarios. In contrast, industrial demand increases in the SG scenario until 2050. This trend compensates the decline in demand from households and CTS at the high-pressure level. Thus, the net length at the high-pressure level does not decrease in the SG scenario.

The costs for decommissioning the gas distribution grids are subject to great uncertainties. We have modeled it by a range of parameters and measures based on recent studies. One crucial assumption is the ratio of the different measures: in the high-cost variation, a relatively high amount of the grids is deconstructed (5 %) or filled and sealed (30 %). A higher share of sealing and reduced cost for filling and sealing lead to significantly reduced decommissioning cost. Experts state that a diameter of 400 mm is a relevant factor for changing the necessary measure. This was considered by a higher share of sealing (96.5%) in the lower cost variation [30]. However, more detailed information by specific diameter classes would significantly improve the modeling results.

Furthermore, decommissioning of the gas distribution grid is a long-term task. This goes hand-in-hand with long-term planning and financing issues. Currently, there is no concrete plan for financing the decommissioning. We have assumed a saving as of today to show in what range the annual cost block is. For example, the financing volume can also be secured after realizing the measures. Concrete targets or objectives of the organizations involved would help to allocate the costs more precisely at this point. It would make a difference if they were generated via the current network charges or if they were provided by the public administration from tax revenues. This aspect shows that there is a need for funding and planning standards for decommissioning implementation.

6. Conclusions

We show that it is possible to represent the current gas distribution network infrastructure with sufficient accuracy using a MNA by DINO. However, a better public data base of regional gas grids could help to validate and improve the details of the results. Based on this, we show the development of gas distribution networks for two greenhouse gas neutral pathways. Two scenarios are used to illustrate the possible range of development. On the one hand, a scenario with a high share of synthetic gases in 2050 is used. The other development extreme is an all-electric scenario.

The infrastructure analysis by DINO shows a declining need for gas distribution networks for all given greenhouse gas neutral scenarios. In the EL scenarios, the network length of the required grid infrastructure decreases to zero by 2050. Even high shares of synthetic methane in space heating get along with a decreased gas distribution network infrastructure. In such moderate scenarios for the gas sector the gas distribution network is reduced extensively compared to today's grid. Furthermore, between both scenarios, the EL and the SG scenario, path differences are observed form 2030. The network decline in the EL scenario is already stronger and accelerates thereafter.

The costs associated with decommissioning have potential for further investigation. A more accurate breakdown of costs by diameter could reduce the uncertainties. However, there are currently no realistic cost estimates since network shutdowns have not been realized. Numbers from real decommissioning projects should be expected in the future.

We also did not consider efficiency gains at specific connection points to be able to look at the pure effect of the decline in demand. We show that demand is the main driver of the grid development. An increasing efficiency at the demand side (e.g., better technology, building insulation) could lead to more supplied consumers. If more consumers need to be supplied, more gas distribution grids may be necessary. However, this would probably not compensate the expected trend of declining gas distribution networks.

Furthermore, as it is part of the public discussion, we could investigate the effects of the use of hydrogen in space heating. This would require modelling the conversion of the gas distribution grids to hydrogen distribution grids. DINO would have to be adjusted to the gas properties of hydrogen. The network elements could stay the same, but cost must be adjusted. Also, the conversion cost of pipeline segments to hydrogen must also be considered. It is difficult to make an estimate due to the lack of studies; however, it can be assumed that there will also be a decline in demand. Thus, a comparable development to synthetic methane is expected, but costs should be higher due to the additional conversion cost of grid elements.

The results of this paper can be used to support the necessary measures to ensure the contribution of gas distribution networks towards greenhouse gas neutrality. Based on the results, current and future grid expansion projects should be questioned. Due to the infrastructure reduction in all scenarios, there is a risk that today's investments come with potential for lock-ins or sunk costs. Furthermore, funding and planning standards for decommissioning in gas distribution grids are necessary to give the affected businesses planning security.

Author Contributions

J.G. and T.S. both developed the methodological approach and surveyed the data for the validation with the support of Ja.H. Together with J.M.-K., they developed the general concept and approach of the paper. A.K. and T.S were the main developers of the DINO / MNA code with the support Je.H and M.W. The input data was derived and prepared by Je.H., J.G., and F.v.M.-R. The main parts are written, and visualisations created by J.G. and T.S. with the support of A.K and Ja.H. M.W., J.G. and J.M.-K. initiated the research and managed the editing process. All authors have read and agreed to the published version of the manuscript.

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Appendix

Parameter	description	Value	unit
Lambda	Pipe roughness	0.026	
Km	Compressibility Factor	0.91	
Rho_{norm}	Density	0.783	[kg/m3]
P_{norm}	Pressure	1.01325	Bar
T_1	Temperature	285	K
T_{norm}	Temperature	273	K
condition number calorific value	Gas specific value transformation	10	
Coincidence factor	Coincidence of peak load	0.9	

Table 4: Specific parameters used in DINO to model the German gas distribution networks based on Cerbe et al. [9] and Kirchner et al. [46]

standard diameter	diameter	Cost [€/km]	Used in Loop 1	Used in Loop 2
DN32	0.026	5.26	yes	yes
DN40	0.0326	6.1	yes	yes
DN50	0.0408	7.4	yes	yes
DN63	0.0514	9.9	yes	yes
DN75	0.0614	12.38	yes	yes
DN90	0.0736	16.66	yes	yes
DN110	0.090	22.55	yes	yes
DN125	0.1022	27.44	yes	yes
DN140	0.1146	33.5	yes	yes
DN160	0.1308	45.94	yes	yes
DN180	0.1472	56.68	yes	yes
DN200	0.1636	68.43	yes	yes
DN225	0.184	81.06	yes	yes
DN250	0.2046	83.4	no	yes
DN280	0.2292	95.16	no	yes
DN315	0.2578	108.9	no	yes
DN355	0.296	124.59	no	yes
DN400	0.3274	142.25	no	yes
DN450	0.3682	161.87	no	yes
DN500	0.4092	181.49	no	yes
DN630	0.5156	232.51	no	yes

Table 5: Applied pipeline diameters and specific cost to model the German gas distribution networks based on Cerbe et al. [9] , frank GmbH [47] and Kirchner et al. [46].