Shrinking together and pulling apart: the Austrian gas grid by 2040 under declining natural gas demand and increasing domestic renewable gas generation

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Abstract

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1. Introduction

In Europe, the most efficient way of transporting natural gas has been piped and grid-related transport for decades. There are two main reasons for this. First, natural gas has been a cheap energy source due to its unlimited availability through imports from bordering regions. Hence, large quantities of natural gas have been demanded to cover various energy services. Second, the transport of natural gas through pipelines over short and long distances has been technically efficient and economically cheap because of good flow conditions regarding pressure levels and, thus, transport capacities [1]. In the context of piped natural gas supply, Austria has a long tradition. Austria was one of the first Western European countries connected to natural gas pipelines. The "Trans Austria Gas Pipeline" (TAG) started operation in 1968 and connected Austria with Slovakia [2]. The natural gas came from Russia. The consequences of this long history of natural gas in Austria are reflected in a high dependence on natural gas in providing energy services [3] and a well-developed gas grid in the country [4].

However, natural gas grids face an uncertain future, as does the Austrian gas grid. European and national decarbonisation policies are pushing the use of natural gas towards renewable energy alternatives in all energy services. The consequence is a massive reduction in demand for natural gas [5]. It is therefore unclear to what extent gas grids will still be needed. The main objective of this paper is to contribute to this discussion by quantifying the scope and size of the Austrian gas grid by 2040 under different decarbonization scenarios. In particular, the goal it to answer the following two research questions:

- How does Austria's natural gas grid today develop up to 2040 under different decarbonization scenarios, ranging from electrification of most of energy services to importing large amounts of renewable methane?
- How do customer grid charges change in a gas grid with a dominant supply of domestic renewable gas generation in Austria, while natural gas demand is significantly declining compared to the status quo?

The analysis of the Austrian gas grid provides relevant insights for countries with a high potential for domestic renewable gas production in the future, such as Germany, Italy, and France (see in [6]). Furthermore, the relevance of this case study must also be considered from a European perspective. The Austrian gas grid has historically been an important hub for the transmission and distribution of imported natural gas through Europe and provides ample storage capacities (see in [7]). Therefore, changes in the Austrian gas grid might also impact the gas grid of neighboring countries and vice versa.

A mixed-integer linear optimization approach is proposed to answer the research questions. The applied model considers the existing natural gas grid as a starting point and decides whether the grid covers the gas demand and whether domestic renewable gas production (i.e., biomethane) is injected into the grid. The model considers the existing pipelines' age and the necessary replacement investments if they reach their technical lifetime and the option of early decommissioning in case of no or insufficient use of pipelines to reduce grid operating costs. The study of four different scenarios ("Electrification", "Green Gases", "Decentralized Green Gases", and "Green Methane") ensures robustness while covering a wide range of possible future gas volume developments in demand, imports, exports, and generation. Therefore, the scenarios and work must be understood from a "what-if" perspective. The scenarios determine the shares of renewable/natural gas, hydrogen, power, and other energy carriers in the energy system. Based on that, the need for pipelines to transport and balance gas demand and generation is analyzed. No blending is considered. Explicitly, no integrated energy system modeling across energy sectors/carriers or analysis of how fossil fuel-based energy services are decarbonized is done.

The paper is organized as follows. Section 2 provides relevant literature on the topic and the novelties of this work. Section 3 explains the applied method and the four scenarios in detail. Section 4 present the results of the work, while Section 5 provides a synthesis of key findings. Section 6 concludes and outlines future research.

2. State-of-the-art and progress beyond

This section discusses relevant scientific literature in the field of this work. It is divided into three parts. First, Section 2.1 deals with the global and cross-country dimension of natural and renewable gas trade. It focuses on the impact of the decarbonization on gas markets and discusses also intra-country gas supply with a high spatial granularity of a grid representation. Then, Section 2.2 examines different approaches of modeling gas grids. Section 2.3 elaborates on the regulation of gas grids and especially on gas grid charges. Finally, Section 2.4 highlights the novelties of this work. Due to the complexity of the topic and the associated magnitude of possible relevant literature, what is not part of the literature review is briefly discussed. Hier beschreiben was nicht part ist.

2.1. Decarbonized gas markets and cross-country trade

In 2021, the European Commission has published a proposal for a framework of renewable and natural gases and for hydrogen [8]. The aim is to support renewable and low carbon gases (i.e., biogas, biomethane, renewable and low carbon hydrogen as well as synthetic methane) in Europe and to reach a share of two-third of gaseous fuels in 2050 energy mix. Further details on the definition of renewable and low carbon gases can be found in [9]. The remaining one-third of gaseous fuels in 2050 is expected to be still fossil natural gas, but in combination with carbon capture, storage and utilization. Today, renewable and low carbon gases have only a minor contribution to Europe's energy mix. Bertasini et al. [10] give a critical overview of the contribution of renewable gases to the decarbonization of the European energy system and grids. Kolb et al. [11] focus in their work on the integration of renewable gases into gas markets. In addition, the latter study provides also a comprehensive literature review on the topic of renewable gases. Lochner [12] elaborates on the European gas market and the identification of congestions in the gas transmission grid. Gorre et al. [13] deal exhaustively with future renewable gas generation costs.

A key role in the transition to renewable and low carbon gas markets has the existing gas infrastructure. On the hand, the repurposing of existing pipelines especially at the transmission grid level allow to build up a hydrogen grid, as proposed in the so-called "Hydrogen Backbone" [14]. In this context, also the recently extended terminal capacities for liquified natural gas (LNG) are worth to be mentioned. In the short-term, LNG terminals are used to support Russian natural gas import substitution by fossil LNG imports from exporter countries, such as the United States and Quatar [15]. But in the mid-term, these terminals can be used to import renewable and low carbon gases, supporting the European gas market [16]. On the other hand, the area-wide existing pipelines of the distribution grid levels (high-, mid-, and low-pressure pipelines) allow the injection of distributed renewable and low carbon gas generation [17]. Sulewski [18] explore the biomethane market in Europe. Schlund and Schönfisch [19] analyze the impact of renewable quota on the European natural gas markets. Paturska et al. [20] provide an economic assessment of biomethane supply system based on the natural gas grid. Khatiwada [21] elaborate on barriers of the decarbonization of natural gas systems. Stürmer [22] examines in detail on the potentials of renewable gas injection into existing gas grids.

2.2. Gas grid modeling approach (top-down and bottom-up)

The following literature review focuses on the modeling of natural gas transport by grids and pipelines. There are other ways of transporting natural gas. The interested reader is referred to Thomas and Dawe [1] for a comprehensive review of the options for transporting natural gas. In general, the literature on gas grid modeling approaches can be divided based on two key dimensions: (i) modeling perspective (e.g., techno-economic) and (ii) spatial scale. These dimensions, along with others such as the sectoral dimension (whether or not hydrogen is accounted for in detail), determine the level of consideration given to various factors such as flow conditions of natural gas, pressure levels and drops in transport pipelines, and the operational energy and costs associated with compressors.

A review on optimization of natural gas transportation systems is given by Ríos-Mercado and Borraz-Sánchez [23]. It encompasses both transmission and distribution grids. Pfetsch et al. [24] elaborate in detail on the operation of gas transmission grids. Pambour et al. [25] propose an integrated transient model approach for simulating the operation of transmission grids. The transient process in transmission grids is further examined by Liu [26]. Riepin et al. [27] develop in their study an adaptive robust optimzation model for transmission grid expansion planning. Chiang and Zavala [28] investigate the interconnection between gas and power transmission grids. O'Donoghue et al. [29] examine transmission pipelines' resistance to high-pressure levels. Liu et al. [30] study aspects of supply security in detail.

With regard to the distribution grid level, Herrán-González et al. [31] provide a comprehensive review on the modeling and simulation of gas grids. Barati et al. [32] propose an integrated framework for grid expansion planning. Giehl et al. [33] examine the impact of the decarbonization on gas distribution grids. Zwickl-Bernhard and Auer [34] present alternative supply options to natural gas distribution grids. Keogh et al. [35] review technical and modeling studies of renewable gas generation and injection into the distribution grid. The same authors present also a techno-economic case study for renewable gas injection into the distribution grid in [35]. Abeysekera et al. [36] analyze the injection of renewable gas in low-pressure gas grids from a technical perspective in detail. Mertins et al. [37] examine the competition between renewable gas and hydrogen injection into distribution grids. Repurposing of natural gas pipelines for hydrogen transport is assessed by Cerniauskas et al. [38]. An overview of the modeling of hydrogen grids is given by Reuß et al. [39].

Finally, the modeling contributions of the open-source community subject of gas grids are discussed. In principle, open-source approaches are becoming increasingly important in energy system analysis [40]. This trend is also continuing in the area of gas grids. For instance, Schmidt et al. [41] provide a set of publicly available gas grid instances that can be used by researchers in the field of gas transport. Pluta et al. [42] present an approach for developing an open-source model of the gas transport grid in Europe. Nevertheless, data on natural gas grids in particular are rarely made publicly available. There are isolated exceptions, e.g. for the transmission grid (see [43] for open-source data on the European transmission gas grid) or for the Belgian gas grid in [44]. However, there is often an information advantage for those who have this information (e.g., gas grid operators) to scientific researchers, particularly with analyses at the distribution grid level.

2.3. Decarbonized gas grid regulation

2.4. Novelties

3. Method

This section describes the methodology of the paper. First, in Section 3.1, the optimization model used is explained in detail. The focus is thereby on the mathematical formulation. However, where meaningful, qualitative explanations are added to give the reader a more complete understanding of the model. These qualitative explanations are used in particular to describe the main decision made by the model between maintaining operation, decommissioning or making replacement investment in existing gas grid pipelines. In Section 3.2, the gas grid in Austria, which serves as the case study in this paper is presented. Then, in Section 3.3, the four different scenarios are shown. Finally, Section 3.4 provides information on the data used, while Section 3.5 takes a critical look at the method and discusses some limitations and their impact on the results.

3.1. Optimization model

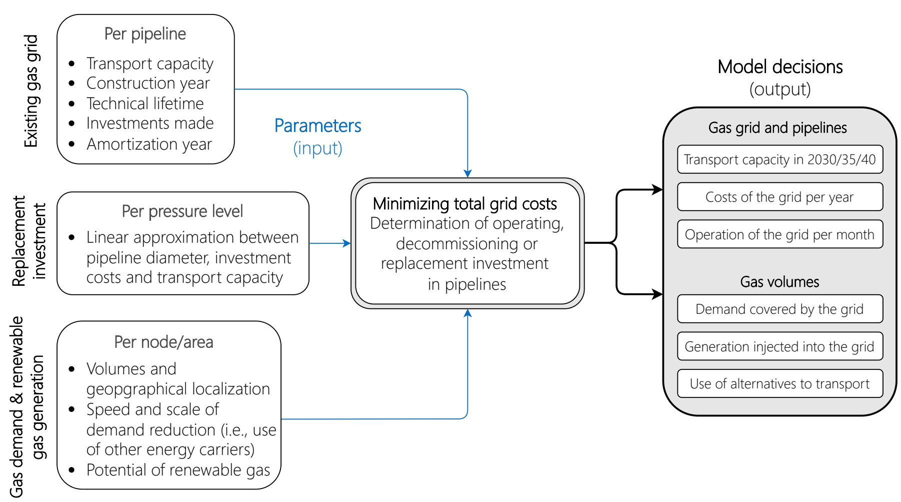


Figure 1

3.1.1. Overview

3.1.2. Objective to minimize total grid costs

3.1.3. Operation, decommissioning or replacement investment in pipelines

3.1.4. Further constraints

3.2. Existing gas grid in Austria

3.3. Scenarios

3.4. Data

3.5. Limitations

4. Results

This section shows the main findings of the Austrian case study. As described above, results for the four scenarios Electrification (Elec), Green Gases (GG), Decentralized Green Gases and Green Methane (GM) are presented. It is structured in three parts. First, Sections 4.1 and 4.2 present the Austrian gas grid in 2030 and 2040 respectively. The quantitative results for grid length, operating and investment costs are presented for both target years in detail. Building on this, Section 4.3 focuses on the costs of the grid and elaborates on the grid charges for customers in 2040.

4.1. Austrian gas grid in 2030

The Austrian gas grid in 2030 is shown in Figure 2. It is the same in all four scenarios and is very similar to the initial grid in 2025, only slightly smaller.

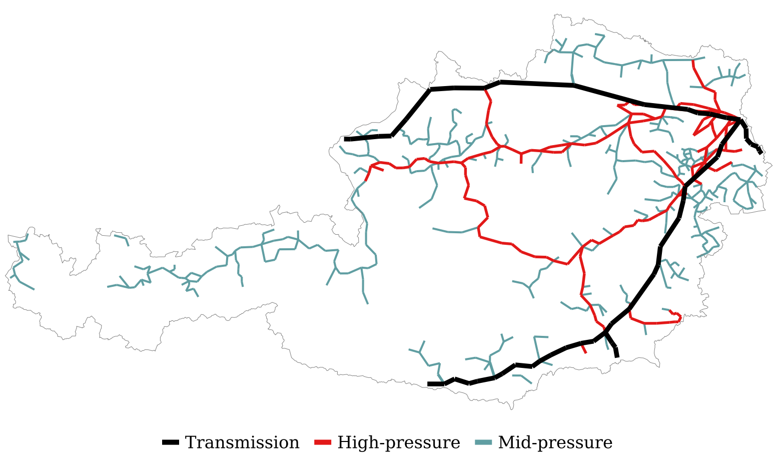


Figure 2: Austrian gas grid in 2030 at the transmission (blue), high-pressure (red) and mid-pressure (green) pressure levels in all four scenarios.

The main reason for the slight reduction of the grid length is the use of redundancies and duplicate structures in the grid as a result of declining gas demand.

Table 1 shows the reduction in the grid length at the high-pressure and mid-pressure levels in the four scenarios.

	2025	2030			
Pressure level	Initial grid	Elec	GG	DGG	GM
High-pressure	1449 km	−172 km (−11.9 %)	−142 km (−9.8 %)	−142 km (−9.8 %)	−131 km (−9.0 %)
Mid-pressure	3218 km	−283 km (−8.8 %)	−200 km (−6.2 %)	−186 km (−5.8 %)	−208 km (−6.5 %)

Table 1: Absolute and relative reduction in the length of the gas grid at the high-pressure and mid-pressure levels by 2030 compared to the initial grid in 2025. Abbreviations: Electrification (Elec), Green Gases (GG), Decentralized Green Gases (DGG), Green Methane (GM).

The reduction in the grid length at the high-pressure level varies between −131 km and −172 km in the GM and Elec scenarios respectively. The reduction in the grid length at the mid-pressure level varies between −186 km and −283 km in the DGG and Elec scenarios respectively. Removing redundant gas pipelines reduces the operating costs of the grid.[1] The operating costs of the gas grid, which are mainly fixed pipeline costs, decrease compared to the initial grid in 2025 and are around 110 MEUR in all four scenarios in 2030. Note that energy costs for the compressor are not included. By 2030, virtually no gas pipelines are decommissioned due to ageing or because the pipeline is no longer used to transport gas. The rather young Austrian grid age also leads to very low replacement investments into the gas grid. In total, those investments vary by 2030 between 15 MEUR and 18 MEUR in the Elec and GM scenarios respectively. Note that in the model presented in this paper, replacement investment is necessary when a pipeline reaches its technical lifetime of 75 years. At this point, the model decides whether to invest in replacing the pipeline or to decommission it age-related.

[1] In reality, these gas pipelines, especially at the transmission and high-pressure levels, can form the core of a hydrogen network. For further details, see for example, the plans for the Austrian hydrogen grid by 2030 published by the Austrian gas network operator [45].

4.2. Austrian gas grid in 2040

The Austrian gas grid in 2040 differs significantly between the four scenarios. Four different gas grids emerge, which are mainly determined by the assumptions of the underlying scenarios. Figures 3 (Elec scenario) and 4 (GM scenario) show the smallest and largest gas grids in terms of grid length.

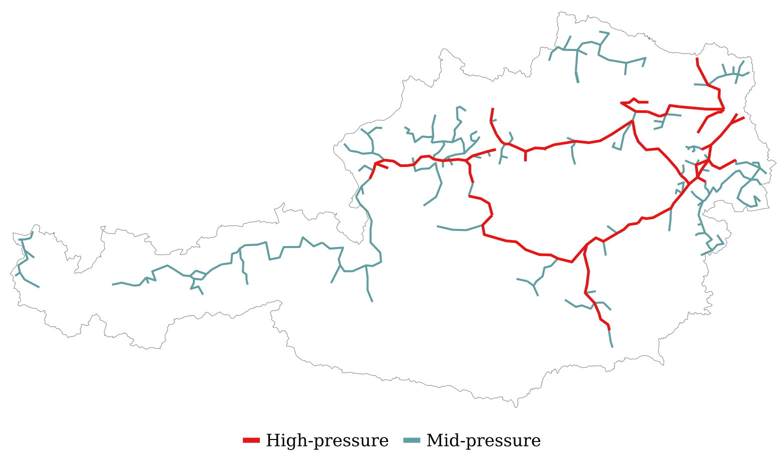


Figure 3: Austria's smallest gas network by 2040 in the scenario Electrification (Elec). Colours: transmission (blue), high-pressure (red) and mid-pressure (green).

The smallest grid is in the Elec scenario and the largest in the GM scenario. The gas grids of the remaining two scenarios GG and DGG are shown in Appendix A. They lie between the two extreme grids in terms of size. Table 2 quantifies the size of the gas grids in 2040 in all the four scenarios by comparing the absolute length of the grids as well as the absolute and relative reduction of grid lengths compared to the initial grid in 2025. In absolute numbers, the reduction of grid length at the mid-pressure level is more significant than at the high-pressure level. In particular, the reduction in the grid length at the mid-pressure level is equally greatest in the two scenarios Elec and GG with $-1316\,\text{km}$ ($-40.9\,\%$ compared to the initial grid in 2025). The smallest reduction in length at the mid-pressure level among the four scenarios is with $-811\,\text{km}$ ($-25.2\,\%$ compared to the initial grid in 2025) in the DGG scenario.

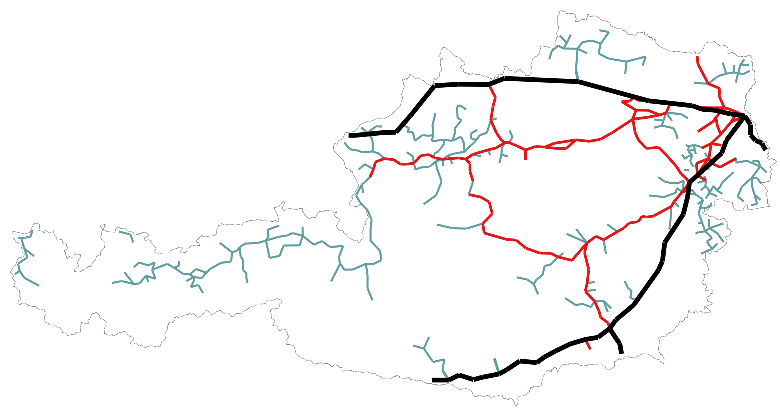


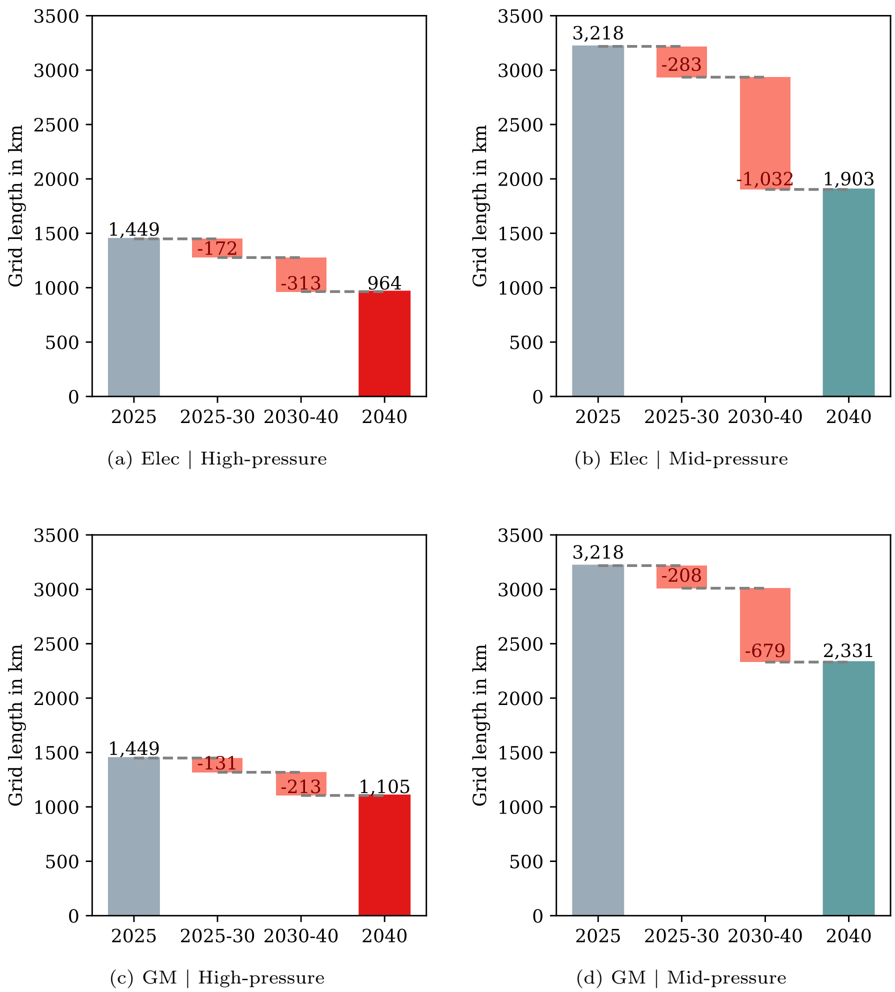
Figure 4: Austria's largest gas network by 2040 in the scenario Green Methane (GM). Colours: transmission (blue), high-pressure (red) and mid-pressure (green).

The main reason here for the relatively small reduction in the mid-pressure grid length is the significant decentralized production and injection of domestic renewable gas.

		2040			
Pressure level	Indicator	Elec	GG	DGG	GM
High-pressure	Abs. grid length in 2040	964 km	965 km	974 km	1105 km
	Abs. reduction to 2025	−485 km	−484 km	−475 km	−344 km
	Rel. reduction to 2025	−33.5 %	−33.4 %	−32.8 %	−23.7 %
Mid-pressure	Abs. grid length in 2040	1902 km	1902 km	2407 km	2331 km
	Abs. reduction to 2025	−1316 km	−1316 km	−811 km	−887 km
	Rel. reduction to 2025	−40.9 %	−40.9 %	−25.2 %	−27.6 %

Table 2: Absolute length of the grids 2040 in the four scenarios as well as the absolute and relative reduction of grid lengths compared to the initial grid in 2025 at the high-pressure and mid-pressure levels. Abbreviations: Electrification (Elec), Green Gases (GG), Decentralized Green Gases (DGG), Green Methane (GM).

The domestic injection leads to an increased use of mid-pressure pipelines. Figure 5 shows the grid length in the two extreme scenarios Elec (top) and GM (bottom) at high-pressure (left) and mid-pressure (right) levels. It highlights the reduction in grid length by 2030 and 2040. The grid length in 2025 is shown on the far left and in 2040 on the far right.



(a) Elec | High-pressure

(b) Elec | Mid-pressure

(c) GM | High-pressure

(d) GM | Mid-pressure

Figure 5: Comparison of the Austrian gas grid in 2025 and 2040 in the extreme scenarios Electrification (Elec) and Green Methane (GM) at high-pressure and mid-pressure levels. In the Elec and GM scenarios, the smallest and the largest gas grids are obtained in terms of the size of the grids.

The operating costs of the gas grid decrease compared to 2025. They vary between 87.5 MEUR and 93.0 MEUR in the Elec and GM scenarios respectively.

50.0 MEUR (the same in all four scenarios) are accounted for the transmission level. The remaining costs are accounted for the high-pressure and mid-pressure level. Figure 6 shows the total replacement investments in the gas grid in the four scenarios. It includes the replacement investments in 2030 mentioned in Section 4.1 above. The lowest total replacement investments are in the scenarios GG and Elec with 143.0 MEUR and 146.0 MEUR respectively. The highest replacement investments are in the GM scenario with 185.0 MEUR.

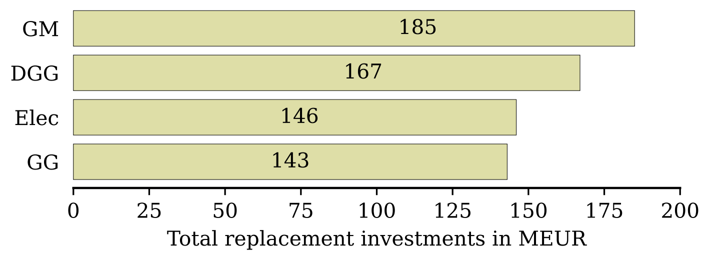


Figure 6: Total replacement investments in the Austrian gas grid until 2040 in the four scenarios.

4.3. Grid charges for customers in 2040

This section presents an analysis of the cost-effectiveness of the gas grid in four different scenarios. The average grid costs are calculated by dividing the total annual grid costs by the gas demand supplied. These average grid costs serve as a basis for estimating grid charges for customers in 2040. It should be noted that determining grid charges based on minimizing system costs must be viewed with caution, as a grid charge regulation process must also be take other considerations into account. Nevertheless, regulatory mechanisms often rely on approaches that aim to minimize system costs. Therefore, it is important to consider and interpret the following results from this perspective. In particular, the different grid costs provide a different perspective on comparing the four scenarios.

Figure 7 shows the (average) grid costs in 2040 in the four different scenarios. Note that the horizontal axis is the renewable gas demand supplied by the grid in TWh. The Elec scenario is therefore on the far left, as it has the lowest gas demand of the four scenarios. At the same time, the GM scenario, which has the highest gas demand among the scenarios, is on the far right.

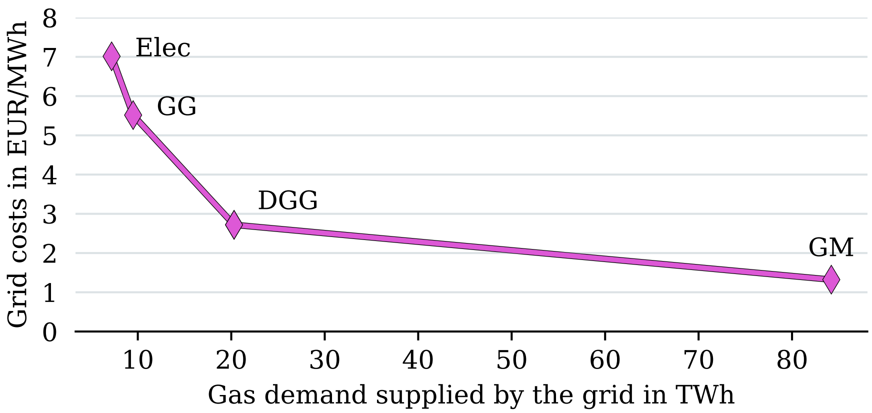


Figure 7: Grid costs in the four scenarios Electrification (Elec), Green Gases (GG), Decentralized Green Gases (DGG) and Green Methane (GM).

It is shown that the grid costs are the highest in the Elec scenario with 7.0 EUR/MWh and the lowest in the GM scenario with 1.3 EUR/MWh. The grid costs and its components of operating costs at the different pressure levels and gas demand supplied are summarized in Table 3.

	2040			
Components for calculating grid costs	Elec	GG	DGG	GM
Transmission operating costs in MEUR	0	0	0	50
Distribution operating costs in MEUR	37.5	39.3	40.2	43.0
Capital costs per year in MEUR	13.0	13.1	15.0	18.3
Gas demand supplied in TWh	7.2	9.5	20.3	84.2
Grid costs in EUR/MWh	7.0	5.5	2.7	1.3

Table 3: Average grid costs and their components of operating costs and capital costs. The distribution operating costs encompass the high-pressure and mid-pressure levels. Separation between the transmission and distribution grids result in accounting no transmission operating costs for the customers.

Note that the three scenarios Elec, GG and DGG assume a separation between the transmission and distribution grids (i.e., high and medium pressure levels). Therefore, the transmission operating costs accounted for customers in these scenarios are zero. Consequently, it is assumed that customers requesting gas transport through Austria at the transmission level bear these costs.

A comparison of the average grid costs with the current grid charges in Austria shows that these are increasing significantly in three of the four scenarios. The current grid charges at the mid-pressure level in Austria are around 1.7 EUR/MWh [46]. Only in the GM scenario, where the supply depend on massive renewable imports, do the grid costs remain around or slightly below this value. In the results of the other three scenarios, the increase in grid costs is driven by the high operating costs of the distribution grid with comparatively low demand volumes and capital costs. The (annual) capital costs in 2040 result essentially from the replacement investments made by then, which are necessary due to the aging of the (otherwise already fully depreciated) existing grid. As mentioned, a technical lifetime of the pipelines of 75 years is assumed. A possible window for reducing grid costs opens, as a more extended operation of pipelines (e.g., technical lifetime between 90 and 100 years) could reduce the share of capital costs in the grid costs; in extreme cases even go towards zero. Such a measure of a longer operating life of pipelines is certainly considered in practice, especially against the background of declining transport volumes. This is because transport volumes determine the operating pressure levels, which determine the pipelines' wear and tear. Lowering the operating pressure levels compared to today's could extend the technical lifetime[2]. Replacement investments due to aging could be saved. Figure 8 shows the impact on the grid costs if an extension of the pipelines' technical lifetime to 90-100 years is taken into account. The lifetime extension leads to no replacement investments and the current pipelines can remain in operation. The grid costs are consequently

[2]In addition, lowering the operating pressure levels also affects and supports domestic renewable gas generation. On the one hand, generation plants require less energy to compress their gas, and on the other hand, their connection costs are reduced, as the costs are highly dependent on the pressure levels in the grid. For more information from the field, see [47].

going down in all the four scenarios. The highest reduction in grid costs is with $-1.8\,\mathrm{EUR/MWh}$ in the Elec scenario. The latter is the one with initially the highest grid costs. The smallest reduction in grid costs is with $-0.2\,\mathrm{EUR/MWh}$ in the GM scenario.

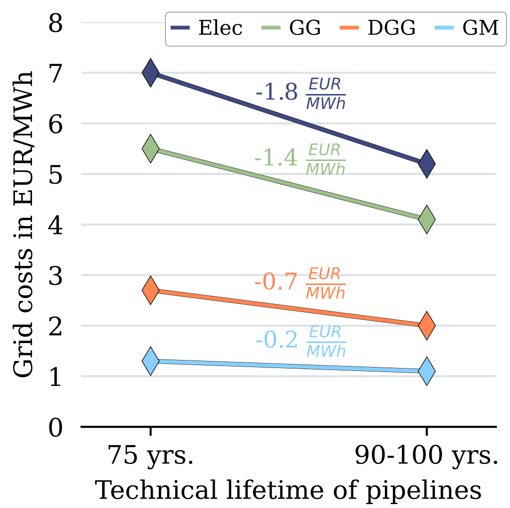


Figure 8: Comparison of grid costs in 2040 for a technical lifetime of pipelines of 75 years (left) and 90-100 years (right).

5. Synthesis

6. Conclusions

was es wert diese analyse durchzuführen: nicht nur mengen, sondern auch einspeisung und deren verortung.

die zukunft von erdgasnetzen bleibt eine der spannendsten fragen die sich durch die umsetzung der dekarbonisierung ergibt.

unbestritten, wird es zu einer verkleinerung der erdgasnetze kommen.

auf der fernleitungsebene sehr eindeutig, dass eine umwidmung zu wasserstoff möglich ist, weil kapazitäten vorhanden sind. parallelstränge erlauben es

auf der verteilnetzebene nicht mehr so eindeutig.

doppelstrukturen herauslösen weil netz oft redundanzen hat.

setzt man auf biomethane große netze weiter gebraucht.

dabei kommt es weniger auf die absoluten mengen an, sondern die verteilte einspeisung ist eher eine ja/nein entscheidung

teurere netze, selbst im elektrifizierung noch ein großes netz

schaffen regional/lokal biomethan, genau abgestimmt wo weiterhin verbrauch bleibt

zukünftige arbeiten, diese regionalen cluster zu identifizieren weitere technische details berücksichtigen, wie die druckentwicklung in schwächer ausgelasteten netzen, energie die gebraucht wird um druckhertzstellen, etc.

Declaration of interests

None.

Data availability

The original data used in this study are publicly available. The compiled dataset is published on Zenodo at Link einfügen!.

Code availability

The code is published under an open license on GitHub at Link einfügen!.

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Appendix A. Detaillierte Gasnetz im Szenario A und B 2040