Designing a model for the cost-optimal decommissioning and refurbishment investment decision of gas networks: application on a real test~~-~~ bed in Austria until 2050

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Abstract

The ~~core objective~~primary goal of this paper is to investigate the most cost-~~optimal decommissioning~~effective decommissioning and refurbishment investment decision ~~of~~for gas networks. An optimization model is developed~~, which is applied to~~ and tested on a real~~-~~ test bed in an Austrian federal state. The analysis is ~~carried out~~performed from the network operator~~'~~'s perspective and ~~shows~~depicts different network decommissioning or refurbishment options under the decision of supplying or not supplying available gas demands. ~~We~~Whether or not there is ensured supply, we find that smaller gas networks (in terms of pipeline capacity and network length) are needed in the future~~ regardless of ensured supply or not.~~. Analyzed shadow prices indicate that a balance/trade-off between the cost-optimal gas network design with and without ensured supply could lead to a robust and economically competitive future ~~of~~for downsized gas networks. The results demonstrate that it is necessary to socialize network operators~~'~~' costs among the remaining consumers connected to the network in the future. ~~That brings an additional~~This adds a cost component to consumers, which ~~needs to~~must be considered when ~~dealing with~~determining the profitability of sustainable alternatives ~~substituting~~to natural gas.

Keywords: Gas networks, decommissioning, modeling, cost-optimal, decarbonization

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Nomenclature

Type	Description	Unit
Set and ~~I~~index		
p e V = {1, ~~...~~…, P}	Pipeline for gas transport, index by p	
n e N = {1, ~~...~~…, N}	Node of the gas network, index by n	
l e L = {1, ~~...~~…, L}	Gas network level (e.g., high-pressure), index by l	
y e Y = {1, ~~...~~…, Y}	Years, index by y	
m e M =	Months, index by m	
Primal Decision Variables (Selection)		
Capex	Capital expenditures	EUR
Opex	Operational expenditures	EUR
Rev	Revenues generated by gas supply	EUR
$l_{p,i,y}$	Capacity of pipeline p at l in y	MW, GW
$q_{n,l,y,m}$	Gas demand supplied at n and l in y and m	MWh, GWh
$q_{p,l,y,m}$	Quantity of gas transported at p and l in y and m	MW, GW
$n_{p,l,y}$	Book value of pipeline p at l in y	EUR
Dual Decision Variables		
	Cost-optimal shadow price of gas supply without ensured supply at n and l in y and m	EUR/MWh
	Cost-optimal shadow price of gas supply with ensured supply at n and l in y and m	EUR/MWh
Parameters (Selection)		
pre	~~Pre-existing~~Preexisting capacity of pipeline p at l in y	MW, GW
$dmax\ d_{n,l,y,m}$	Maximum gas demand at n and l in y and m	MWh, GWh
a^{fed}	Quantity of gas fed in at n and l in y and m	MW, GW
$inv\ c_l$	Specific refurbishment investment costs at l	EUR/MW/km
$n_{p,l,y}$	Book value of ~~pre-existing~~preexisting pipeline p at n in y	EUR
$y_{p,l}$	Year of refurbishment/decommissioning per p and l	1
CO	Weighted average cost of capital	%
i	Interest rate (for calculating the net present value)	%

1. Introduction

Adherence to the remaining CO_2 budget of the Paris Agreement requires rapid defossilization of the energy system [1]. In Europe, the *Fit for 55* package [2] and the *EU Green Deal* [3] define the mid- and long-term goals for a transition to a sustainable energy supply until the middle of the century. These goals include a reduction of CO_2 emissions by 55% compared to those in 1990 by 2030 and climate neutrality in 2050. ~~Against~~ In light of this ~~background~~, the question ~~arises~~ of the concrete design of measures to achieve these goals arises [4]. Numerous scientific works ha~~r~~ve already been dedicated to the analysis of sustainable alternatives for the provision of energy service needs, which currently rely on fossil fuels. Abas et al. ~~A comprehensive~~[5] provide a comprehensive review of fossil fuels as a primary energy source in the energy supply chain and future energy technologies ~~is exemplarily given by~~ . Corresponding~~Abas et al. [5]. Correponding~~ studies ~~often~~frequently focus primarily ~~focus~~ on the renewable energy technology portfolio that provides energy service needs in the future. We essentially ~~take~~use these as the starting point ~~for the~~of our analysis here ~~and investigate~~, investigating the implications of expected declining coverage of energy services by natural gas, a fossil fuel, on its transmission and distribution network infrastructure.

Natural gas is ~~undoubtedly~~undeniably one of the pillars of existing energy systems, but it is being fundamentally challenged by the already established and ongoing ~~decar-bonization~~decarbonization of energy systems. ~~Even more~~Furthermore, as part of the sustainable transition, natural gas and its role ~~is~~are expected to undergo ~~a deep~~significant transformation ~~as part of the sustainable transition~~.[2] ~~However, at present~~However, presently, it is not clear which exact trajectory natural gas will take until 2050 [7].[3] Two focal reasons/subjects are~~:~~ (i) various energy sectors currently use natural gas in the provision of energy services (e.g., generation of process

[x] McGlade and Ekins [6] stated that half of natural gas reserves should remain unused from 2010 to 2050 in order to meet at least the less ambitious 2.0°C climate target from the Paris Agreement.

[3] Exemplarily, Kumar et al. [8] ~~see~~saw natural gas as an important bridging fuel to a sustainable energy system, in some cases even after 2050. ~~In contrary~~By contrast, Stephenson et al. [9] proposed to abandon the transition fuel characterization of natural gas. Diaz et al. [10] followed this point of view since they find for the electricity sector that natural gas delivers little to no cost savings as a bridging fuel in a system that switches to wind and solar.

heat or as a base material for industrial consumers, centralized generation of electricity and district heating, and decentralized supply of space heating and hot water demands~~)~~), and it is not clear if and when exactly sustainable alternatives will be economically available, implemented, and realized in sufficient quantities [11, 12]. (ii) Synthetic gases (including hydrogen) are seen as a promising alternative or supplement to natural gas us~~e~~age, as they could be fed into existing transmission and distribution gas network infrastructure, although~~,~~ there are valid uncertainties regarding its amount of technical as well as economic potentials [13, 14]. ~~In view~~Because of that, the question is not only which energy sectors and energy services remain to use the limited quantities of natural (following the trend of defossilization) and synthetic (because of limited potentials gas~~),~~) but also what gas network infrastructure will continue to be needed for their transport and distribution.

The ~~scope~~goal of this paper is to contribute to scientific research ~~regarding~~on the future development and trajectory of gas network infrastructure ~~under~~with the expectation of dec~~l~~reasin~~in~~g natural gas demands and ~~the~~ increasing the integration of green gases, such as synthetic gas and hydrogen. The ~~focus lies~~ emphasis is on gas network ~~infrastructure that~~ infrastructure, which ensures ~~the coverage of~~that various energy service needs (e.g., residential building heat~~,~~ and industrial process heat~~). Associated with this is~~) are met. This raises the question of which gas network infrastructure is ~~needed~~required to ~~supply the~~meet non-substitutable natural gas demands ~~under consideration of~~when considering possible stand-alone natural gas supply options (e.g., delivery of lique~~ei~~fied natural gas by truck~~, etc.). Nevertheless~~). Nonetheless, even if stand-alone solutions are ~~poss~~viable alternatives in some cases, arbitrariness regarding the trajectory decisions of gas networks ~~needs to~~must be ~~prevented~~avoided, as they are not only assigned to critical infrastructure but also ~~under regulation~~regulated and subject to long-term energy planning (lock-in effect).

The ~~core~~primary objective of this work is to investigate the most cost-effective trajectory of gas network infrastructure from a systemic ~~point of view~~viewpoint under a long-term planning horizon. ~~In view of~~Given necessary refurbishment investments in existing gas network infrastructure and pipelines due to their technical lifetimes, the main research question is ~~of~~ which decommissioning and refurbishment investment decisions result in a cost-effective gas network infrastructure by 2050.

Equally important in the analysis is the network operator's trade-off decision ~~from the network operator's perspective~~regarding whether available gas demands within the network area are supplied or not, as~~ the~~ decommissioning of existing gas pipelines can be cost-effective~~,~~ but ~~at the same time~~ results in ~~not supplied~~unsupplied gas demands~~.~~. Consequently, three different model runs are performed, allowing for a thorough comparison of various handling options in terms of gas demands not met by network infrastructure. [4] Accordingly, three different model runs are conducted, enabling a comprehensive comparison of different handling options in terms of gas demands not supplied by the network infrastructure. Accordingly, the analysis relies heavily on the shadow prices of gas supply ~~on~~at the local level within the network's nodes ~~play a crucial role in the analysis~~.

The method ~~applied~~used is the development of a linear optimization model. Thereby, the objective function is to minimize the network operator's net present value over time. ~~In particular~~Particularly, the optimal solution of the model includes the decommissioning and refurbishment investment decision of parts of the network and single pipelines. ~~That encompasses the decision of~~This includes deciding whether or not to supply available gas ~~demands are supplied or not.~~demand. The dual variables of the local gas balance constraints ~~at the local level~~ allow us to assess the technoeconomic~~-economic~~ range of supply alternatives for each node ~~w~~i~~thi~~n the network.

The numerical example ~~analyzed~~examined is a small p~~a~~ortion of the existing Austrian gas network infrastructure~~, which is located~~ in the NUTS2 region Vorarlberg, Austria. This area ~~can be characterized~~is distinguished by ~~diversified~~ a wide range of energy service ~~needs~~requirements that are ~~supplied~~met by natural gas (e.g., residential~~,~~ and industry~~, etc.). In addition~~). Furthermore, the gas network infrastructure ~~encompasses~~includes not only ~~the~~ high- and mid-pressure network ~~level,~~ connections but also ~~crossboder~~cross-border connections to ~~the neighbouring~~neighboring countries Germany and Lichtenstein (i.e., transmission network level). There ~~ex~~is~~ts~~ also the ~~potential~~possibility of producing green gas ~~production~~ and ~~injection~~injecting it into the existing gas network infrastructure.

[4] Grid operator usually is a regulated entity. ~~Therefore~~Thus, finally, it is a regulatory question/decision, which cannot be taken by the grid operator alone (regulator).

The paper is organized as follows. Section 2 provides an overview of the current state~~-~~ of~~-~~ the~~-~~ art in scientific literature and outlines the novelties of this work beyond existing research. Section 3 presents the materials and methods developed in this work, including~~, among others,~~ the model's mathematical formulation and description of different model runs. Section 4 presents the results of this work encompassing different handlings of gas demands within the network. Section 5 synthesizes and discusses the results, concludes the work, and gives an outlook for future research.

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

This section provides an overview of relevant scientific literature for this paper's scope. It emphasizes two essential subjects, namely, the role of natural and green gases in sustainable energy systems (Section 2.1) and the modeling of gas networks from a system perspective point of view (Section 2.2). ~~Building upon,~~The novelties of this work and progress beyond state~~-~~ of~~-~~ the~~-~~ art are also presented

(Section 2.3).

2.1. Natural and green gases in sustainable energy systems

~~Whether~~It is debatable whether natural gas will ~~make an important contribution to~~play a significant role in the energy ~~transition in~~transition over the next few decades, and if so, under what conditions~~, is a divise subject. A~~. Gursan and Gooyert [15] provided a recent and ~~compact~~concise review of the state~~-~~ of~~-~~ the~~-~~ art ~~wi~~thin the role of natural gas in reducing CO_2 emissions ~~of~~from energy systems~~ is given by Gursan and Gooyert [15]~~. Kotek et al. [16] conducted a study on the European natural gas infrastructure in the context of energy transition. Already in 2012, Stephenson et al. [9] discussed natural gas as a transition fuel in the sustainable transformation of energy systems. They concluded that a natural gas climate solution ~~for natural gas~~ is unsubstantiated. This is also reflected in ~~the~~a large number of studies on cost-optimal energy supply until 2050~~ of a large number of studies. Exemplarily,~~. Auer et al. [17]~~ investigate~~, for example, investigated the European energy supply until 2050 for ~~different~~various decarbonization scenarios under the remaining European fraction of the CO_2 budget and ~~find~~discover that natural gas is almost completely replaced in the primary energy demand in 2040.

~~At the same time, and this is shown~~ Green gases are becoming increasingly important, as evidenced by not only ~~by~~ the results of Auer et al. for Europe but also~~, for example, by~~ those of Zhang et al. ~~[18]~~[18] for China~~, green gases are becoming increasingly important.~~. Against this background, it is certainly possible to see existing natural gas networks as a crucial part of the energy transition to transport and deliver green gases. Recently, Quintino et al. [19] elaborated on aspects of green gas introduction in natural gas networks. Dodds and ~~Mc Dowall~~McDowall [20] examined the long-term future of gas networks and stated that the most cost-~~optimal~~effective strategy might be to convert the networks to deliver green gases[5]. Similarly, Mac Kinnon et al. [21] investigated the role of natural gas networks in mitigating greenhouse gas emissions. Gillessen et al. [22] elaborated on the ~~the~~ role of natural ~~g as~~gas as a bridge to sustainable energy systems and related infrastructure expansion of gas networks. Gondal [23] ~~studies the~~studied hydrogen integration into gas transmission networks.[6]

~~Nevertheless, while~~Nonetheless, although the expected potential of green gases exists, it is nowhere large enough to replace the current amount of natural gas in the energy supply. Accordingly, the discussion of existing natural gas networks may and should include decommissioning as part of the solution space. ~~Moreover~~Furthermore, this possibility should no longer be seen as a taboo subject~~,~~ but~~her~~ rather as a real decision option that can even be argued from a ~~techno-economic~~technoeconomic point of view. Giehl et al. [24] examined cost-optimal gas networks and focused particularly on the distribution network level, finding a declining need for gas distribution networks in their future scenarios. Zwickl-Bernhard and Auer [25] presented the decommissioning of a gas distribution network in an urban area at the community level. Feijoo et al. [26] f~~i~~ound risks of ~~under-utilization~~underutilization of gas networks (i.e., pipeline capacities) in a low-carbon future economy even at the ~~inter-state~~interstate and transmission level.

[5] Interestingly, Dodds and McDowall f~~i~~ound in their scenarios that hydrogen injection into gas networks ha~~ve~~s only a small role and low impact on gas networks.

[6] ~~In particular~~Particularly, Gondal state~~s~~d that~~:~~ (i) at the transmission network level, compressors are the determinant element and limit the value of hydrogen by 10~~%,~~%; (ii) at the distribution network level, pipelines and storage elements allow shares up to 50% of hydrogen~~,~~; and (iii) at the level of end use appliances, a tolerant range and share of 20~~ to ~~%–50% of hydrogen is possible.

Brosig et al. [27] compare~~s~~d the cost-effectiveness of different future pathways between expansion and decommissioning of the gas grid network.

In this context, local renewable energy sources and technologies are becoming increasingly important. For example, district heating contributes in densely populated and urban areas to the decrease of natural gas in the supply of energy service needs. Moller and Lund [28] examined the conversion of individual natural gas heating units to district heating. Hofmann et al. [29] showed the use of geothermal sources for ~~the~~ heat generation for both residential and industr~~y~~ial. At the national level, Geyer et al. [30] present~~s~~ed scenarios, energy carriers, and infrastructure requirements for a completely renewable energy-based industry sector. Rahnama et al. [31] ~~shows in particular~~showed particularly the reduction of gas demands and associated CO_2 emission for the pulp and paper industry by electrification of energy service needs. Bachner [32] et al. focused on the replacement of gas and other fossil fuels in the steel and electricity sector from a macroeconomic perspective[7].

Findings of the literature in the previous paragraph indicate that large portions of natural gas demands can, in principle, be substituted by sustainable alternatives. Against this background and ~~taking into account~~considering that natural gas networks are regulated entities of the energy system, are capital intensive, and therefore require long-term strategies or planning, avoidance of stop-and-go policy is crucial. Exemplarily, Then et al. [34] stud~~y~~ied the operator strategy and economic viability of gas networks in face of decreasing gas demands. Hickey et al. [35] identif~~y~~ied significant challenges and risks to policymakers and investors in using gas networks in sustainable energy systems ~~emcompassing~~encompassing the risk of stranded assets, resulting not only from declining gas demands~~,~~ but also from changes in regulation and how tariffs are allocated. ~~-~~Hausfather [36] focuse~~s~~d on the policy

[7] In the context of a decarbonized electricity supply, Qadrdan et al. [33] investigated the impact of transitioning to a low-carbon electricity sector on gas network infrastructure. ~~In particular~~Particularly, the authors focused on the gas network in Great Britain and f~~i~~ound that despite the declining gas demand, the peak gas demand remains unchanged.

decisions for natural gas and its network infrastructure until 2030 as they irreversibly impact the future of natural and synthetic gas in the period 2030 to 2050[8]. Hutagalung et al. [37] dealt with the economic implications of natural gas infrastructure investments. Tata and DeCotis [38] focused on risks and responsibilities associated with natural gas infrastructure develop~~e~~ment. Sacco et al. [39] analyzed maintenance risks associated with gas networks. Sesini et al. [40] assessed resilience and security in gas network systems. The~~y~~ key findings can be summarized ~~as~~since decisions on natural gas infrastructure development should not be made through a single-lens view.

2.2. Modeling gas networks

~~In particular~~Particularly, the previous paragraph regarding the challenges and risks of long-term planning of gas networks provides the starting point for this section dedicated to modeling and simulation of gas networks. R~~l~~oos-Mercado [41] presented a comprehensive state-~~-~~of-~~-~~the-~~-~~art review on the optimization of natural gas networks e~~m~~ncompassing both the transmission and distribution network level. ~~An~~Osiadacz and Gorecki [42] provided an even broader summary of gas network optimization modeling approaches~~ is provided by Osiadacz and Gorecki [42]~~.. Particularly, they mention heuristic, continuous and discrete methods of the optimal design of gas networks. Feijoo et al. [43] proposed a long-term partial equilibrium model that allows for endogenous gas network infrastructure expansion and ~~non-linear~~nonlinear cost functions. Fiigenschuh et al. [44] developed an optimization model with quadratic formulation. Fodstad et al. [45] and Afimann et al. [46] used stochastic optimization including gas demand uncertainties in the optimization of gas networks. Latter use a decomposable robust two-stage optimization model. Von Wald et al. [47] proposed a ~~multi-period~~multiperiod planning framework for decarbonization of integrated gas and electric energy systems.

The long-term planning of gas networks is exemplarily shown by Hubner and

[8] Moreover, Hausfather concludes that policy decisions are needed leading to decarbonization of natural gas no ~~lather~~later than 2030.

Haubrich [48] and Giehl et al. [24]. ~~Latter propose~~The latter proposed a greenfield approach and optimization model for gas networks without considering the existing network infrastructure (i.e., from scratch). Mikolajkova et al. [49] ~~show~~showed the optimization of a natural gas distribution network with the potential future extension of the trans~~-~~mission network level. Kashani et al. ~~The techno-economical~~[50] presented the technoeconomical and environmental optimization of natural gas network operation. Farsi et al. ~~is presented by~~ [51] showed a~~Kashani et al. [50]. A~~ national case study regarding the cost efficiency of gas distribution networks~~ is shown by~~. ~~Farsi et al. [51].~~ Particularly, they emphasized the impact of customer density and network size in the Swiss gas distribution sector. Odetayo et al. ~~Modeling~~[52] showed the modeling flexibilities of gas networks for energy system operation. Dieguez et al. ~~is shown by~~ [53] showed the modeling~~Odetayo et al. [52]. Modelling~~ of decarboni~~s~~zation transition in a national integrated energy system including hourly operational resolution of gas networks~~ is shown by~~. ~~Dieguez et al. [53].~~ Yusta and Beyza [54] emphasized the modeling of large-scale gas storage facilities by a dynamic approach. Kerdan et al. [55] linked a spatially resolved gas infrastructure optimization model with an energy system model.

2.3. Progress beyond the state-of-the-art

Based on the literature review, the novelties of this work can be summed up as follows:

・ A cost-effective trajectory of existing gas network infrastructure is modeled considering the expectation of both declining gas demands resulting from the defossilization of energy services and the increasing but limited integration of green gases, such as synthetic gas and hydrogen.

・ Since existing gas network infrastructure requires ~~for~~the refurbishment of its gas pipelines due to the expiration of the technical lifetime, it is shown how the gas network operator decides from a ~~techno-economic~~technoeconomic point of view between decommissioning and refurbishment investment of gas pipelines at different network and pressure levels. Especially, the transmission, high-pressure, and mid-pressure network levels are analyzed.

• The optimization of a cost-effective trajectory of existing gas network infrastructure includes~~, among others,~~ the gas network operator~~’~~'s decision between supplying or not supplying available gas demand (i.e., disconnection from the gas network by decommissioning gas pipelines and implicitly implementing stand-alone gas supply alternatives). ~~In particular~~Particularly, the long-term planning horizon of the model allows ~~to investigate~~for investigating this ~~trade-off~~trade-off decision between investment/capital costs, related book values, and expected revenue and purchase streams for individual gas pipelines.

• The application of the proposed model on a real test~~-~~-bed in a NUTS2 region in Austria until 2050 provides useful insights that can be used directly by decision and ~~policy makers.~~policymakers. The investigated test~~-~~-bed is ~~representative for~~ representative of other gas networks since it co~~ns~~mpris~~t~~es, on the one hand, ~~of~~ gas demands that are supplied in different end-user sectors~~,~~ and, on the other hand, encompasses different gas network/pressure levels. Accordingly, the transmission network level is also considered as the test~~-~~-bed gas network is linked to neighboring countries.

3. Materials and methods

This section explains the proposed methodology. First, Section 3.1 ~~gives an introduction into~~introduces the model. Then, Section 3.2 presents the mathematical formulation in detail. Section 3.3 explains the different model runs and defined scenarios. Section 3.4 provides the test~~-~~-bed description and shows the gas networks in Vorarlberg, Austria, in detail, and Section 3.5 presents the input data. Section 3.6 discusses the limitations of the model. Finally, Section 3.7 deals with the open-source programming environment and the computation time of the model.

3.1. Introduction ~~into~~of the model

Figure 1 provides an overview of the method, including the interrelationships between the inputs (left), the modeling framework (middle), and the outputs (right). Generally, the inputs (and thus parameters) can be divided into three different categories, namely, technical parameters (e.g., existing pipeline capacity per network/pressure level and the year of construction), economic parameters (e.g., refurbishment investment costs per pipeline), and further empirical data needs (e.g., gas demand and supply at the local community level~~,~~ and seasonal gas storage capacities). The modeling framework (CANCEL) is developed as a linear program and is based on graph theory. It emphasizes the high spatial resolution in modeling. Particularly, a single node in the gas network graph corresponds to a community and covers an area of approxi~~a~~mately 40 km² on average. The temporal resolution and thus investment planning horizon are until 2050, ~~while~~whereas an individual year is monthly resolved. Since the modeling framework is an investment and dispatch model, the outputs can also be divided into these ~~to catergories as well.~~categories. The outputs related to the investment decision are particularly the decommissioning and refurbishment investment decision per pipeline and gas network level. ~~In addition~~Additionally, the outputs encompass the dispatch of the gas networks on a monthly resolution. This includes~~, among others,~~ the utilization of~~ a~~ pipelines and particularly the gas demand and gas demand not supplied per community.

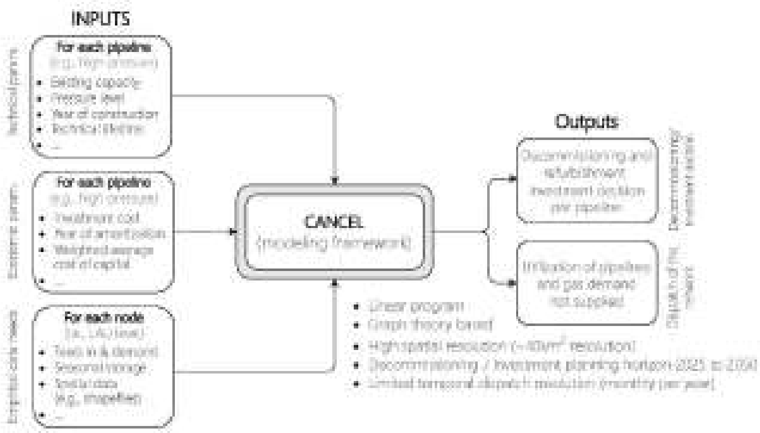


Figure 1: Overview of the method

3.2. Mathematical formulation

This section is dedicated to provid~~e~~ing a detailed mathematical formulation of the modeling framework. We start with the objective function and have deliberately chosen the further order of equations so that the following equation builds on the previous one as far as possible.

Equation 1 shows the objective function of the model where *Capex* is the net present value of the capital expenditures, *Opex* of the operational expenditures, *Rev* of the revenues from the supply of gas demands, and *Purch* of purchasing gas. *Capex* and *Opex* represent the decommissioning and investment decision, whereas *Rev* and *Purch* the dispatch of the gas networks.

$$\min_x Capex + Opex - Rev + Purch \qquad (1)$$

~~Besides~~Additionally, x represents the decision variables of the model. Equation 2 shows the calculation of the discount factor per year y (α_y~~)~~), where i is the interest rate and y_0 is the reference year.

$$\alpha_y = \frac{1}{(1+i)^{y-y_0}} \qquad (2)$$

Building upon, *Capex* is calculated as shown in Equation 3 where u is the weighted average cost of capital and n_y is the book value of the pipelines in y.

$$Capex = \sum_{y}^{y_{end}-1} \alpha_y \cdot \omega \cdot \Pi_y + \underbrace{\alpha_{y_{end}} \cdot \Pi_{y_{end}}}_{\text{early depreciation}} \qquad (3)$$

Similar~~ly~~ly, *Opex* is calculated as shown in Equation 4 where X_y ~~are~~is the fixed (operating) costs of the pipelines in *y*.

$$Opex = \sum_{y} \alpha_y \cdot \lambda_y \qquad (4)$$

Equation 5 shows the calculation of the X_y where c^{fix} ~~are~~is the specific fixed (operating) costs per *I* and *Yi,y* is the installed pipeline capacity per *I* in y.

$$\lambda_y = \sum_l c_l^{fix} \cdot \gamma_{l,y} \qquad (5)$$

Equation 6 shows the calculation of Yl y, where *Yp^^* is the installed pipeline capacity at *p* and *I* in *y* and P_l the subset of all pipelines at l.

$$\gamma_{l,y} = \sum_{p \in P_l} \gamma_{l,y,p} \qquad (6)$$

Equation 7 defines the capacity of a pipeline *p* at *I* in *y*, where is the ~~pre-existing~~ preexisting capacity and Y**p**^e/y is the refurbished capacity of *p* at *I* in y.

Comment [Editor1]: Remark: Missing variable.

$$\gamma_{p,l,y} = \gamma_{p,l,y}^{pre} + \gamma_{p,l,y}^{ref} \qquad (7)$$

Similarly, Equation 8 defines the book value of a pipeline *p* at *I* in *y*, where n**p**^rc l y is the book-value of the ~~pre-existing~~preexisting pipeline (capacity), n**p**^e/y of the refurbished capacity of *p* at *I* in *y*, and the discount factor at *p* and l.

Comment [Editor2]: Remark: Missing variable.

$$\Pi_{p,l,y} = \Pi_{p,l,y}^{pre} + f_{p,l}^{ref} \cdot \Pi_{p,l,y_{p,l}^{inv}}^{ref} \qquad (8)$$

Equation 9 sums the book values of all pipelines and network levels to obtain the total book value per *y* (n_y).

$$\Pi_y = \sum_p \sum_l \Pi_{p,l,y} \qquad (9)$$

The following ~~E~~equation defines the refurbished installed capacity per *p* at *I* in *y* resulting from the refurbishment (or decommissioning) decision in the year of the decision (y**p**"f).

$$\gamma_{p,l,y}^{ref} = \begin{cases} 0 & : \forall y \mid y < y_{p,l}^{inv} \\ \gamma_{p,l,y-1}^{ref} & : \forall y \mid y > y_{p,l}^{inv} \end{cases} \qquad (10)$$

Equation 11 calculates the book value of the refurbishment investment at p and l in y**p7**.

$$\Pi^{ref}_{p,l,y^{inv}_{p,l}} \qquad c^{inv}_{l} \cdot \gamma^{ref}_{p,l,y^{inv}_{p,l}} \tag{11}$$

Equations 12 and 13 define the total gas export and import from n at I in y and m where q_{p}^^$_{m}$ is the amount of gas transported by p at I in y and m. ~~In addition~~Additionally, P^f and P^^{p} define the subsets containing all pipelines that can export and import gas from n at l.

$$q^{exp}_{n,l,y,m} - \sum_{p \in P^{exp}_{n,l}} q_{p,l,y,m} \tag{12}$$

$$q^{imp}_{n,l,y,m} - \sum_{p \in P^{imp}_{n,l}} q_{p,l,y,m} \tag{13}$$

Equations 14 and 15 set the lower and upper bound of the amount of gas transported with respect to the installed pipeline capacity.

$$q_{p,l,y,m} \leq \gamma_{l,y,p} \tag{14}$$

$$-q_{p,l,y,m} \leq \gamma_{l,y,p} \tag{15}$$

The last two equations underline that a pipeline in the model has a certain direction in which the amount of gas transported is counted positively. Therefore, this direction defines for a node n whether a pipeline p is considered positively in the import or export balance (compare Equations 12 and 13). Exemplarily, a pipeline p could be considered in the export sum of a node n on the one hand with a positive value if p in fact exports gas from n but on the other hand with a negative value if p imports gas to n in the dispatch of the model decision[9].

[9]We use this approach to prevent binary decision variables. Particularly, binary decision variables increase the computation time of graph-theory-based models significantly. For more information, we refer to Kotzur et al. [56] and their comprehensive review on how to handle complexity in energy system optimization.

Equation 16 shows the general formulation of the balance constraint at n, where $_{y\ m}$ is the amount of gas from or to ~~a~~ storage. Particularly, this equation is defined for each network level /. The coupling of different network levels (e.g., the high-~~pressure~~ and mid-pressure network levels) is considered implicitly in the definition of the different gas demand variables (see Equation 17 below). ~~In addition~~Additionally, £m is a scaling (or transformation) factor ~~which~~that is defined for each month and is used to couple total values per month (e.g., $_m$) and peak

values.[10]

$$q^{fed}_{n,l,y,m} - q^{dem}_{n,l,y,m} - \xi_m \cdot \left(q^{exp}_{n,l,y,m} + q^{imp}_{n,l,y,m}\right) + q^{sto}_{n,l,y,m} - 0 \qquad (16)$$

Exemplarily, Equation 17 shows the calculation of the gas demand at network level I, where $q^{\wedge}{}_{,\ y\ m}$ is the amount of gas delivered from network level I to I' and q^ryT is the local gas demand supplied at n. For example, I could ~~be~~ correspond to the transmission network level and I' to the high-pressure network level. Note that the pressure in pipelines at I is higher than at /'.

$$q^{dem}_{n,l,y,m} \quad q^{dem,loc}_{n,l,y,m} + q^{del}_{n,l',y,m} \qquad (17)$$

Equation 18 is the essential demand constraint and sets the upper bound of the decision variable qt^T,]™c to the

maximum available gas demand (<£-"f^x T)), in which

Tt, l, y, 7iL ^^ ib, l, y, fib/

is defined as an input parameter.

$$q^{dem,loc}_{n,l,y,m} \leq d^{max}_{n,l,y,m} \qquad (18)$$

~~In particular~~Particularly, Equation 18 allows the model by its mathematical operator with the less than or equal sign (<) to decide between supplied and not supplied gas demand at the nodal level. This decision is in the foreground of the conducted

[10] It reflects the fact that Equation 16 encompasses variables that are associated with nodes~~,~~ $q^{de}T^a$, $q^{st o}$) modeled at a monthly resolution and with lines ($q^{ex}F$, $q^{\prime\prime a}P$) modeled at a hourly resolution.

analysis here, which is why we use particularly Equation 18 to define different model runs and thus scenarios. Accordingly, the model runs and scenarios differ by the individual specification of the demand constraint (i.e., < or = and d^ **y** **m** as the upper bound of the equation). We refer to a detailed description of the model runs and scenarios in Section 3.3.

The (total) quantity of gas fed at l' is defined as stated in Equation 19, where *qn^ym!* is the quantity of gas fed directly from *n*.

$$q^{fed}_{n,l',y,m} - q^{fed,local}_{n,l',y,m} + q^{del}_{n,l',y,m} \quad (19)$$

Equation 20 defines the balance constraint of a storage unit. ~~In contrast~~Contrary to most storage constraints, we do not consider different efficiency values for the charge and discharge. Hence, a single variable can be used. ~~In addition~~Additionally, q^^**T** is the state of charge. *rj* is the storage efficiency and thus models the losses with respect to the storage of gas between ~~two~~2 months.

$$q^{sto,soc}_{n,l,y,m} \quad \eta \cdot q^{sto,soc}_{n,l,y,m \quad 1} + q^{sto}_{n,l,y,m} \quad (20)$$

Equation 21 calculates the revenues created by the local gas demand supplied where *pl°c* is the price.

$$rev_{n,l,y,m} = p^{loc}_{l,y} \cdot q^{dem,loc}_{n,l,y,m} \quad (21)$$

Accordingly, the revenues (Rev from the objective function in Equation 1) are calculated as shown in Equation 22.

$$Rev - \sum_{y}\sum_{n}\sum_{l}\sum_{m} \frac{1}{1 \mid i_o} \cdot rev_{n,l,y,m} \quad (22)$$

Purch is calculated as shown in Equation 23, where p^g<**m** is the gas price in *y* and m.

$$Purch = \sum_{y} \sum_{n} \sum_{m} \frac{1}{1+i_o} \cdot p^{gas}_{y,m} \cdot q^{del}_{n,l,y,m} \quad \text{with } l = \text{high-pressure} \qquad (23)$$

~~In particular~~Particularly, the influence of the gas price in the dispatch of gas networks is considered if gas is delivered from the transmission to the high-pressure network level. This is why Equation 23 is only defined for the high-pressure network level. This simplification is quite justified, first, because the gas storages, whose operation is significantly determined by the monthly gas price, are only present at the high~~-~~-pressure level, and second, because no gas delivery from the high~~-~~-pressure level to the transmission system is possible in the model.

3.3. Model runs and defined scenarios

We conduct three different model runs, whereas each is associated with a scenario. Thereby, the model runs and defined scenarios differ in terms of consideration of the coverage of existing gas demands. Particularly, this is achieved by the modification and tailor-made adaption of the gas demand constraint in Equation 18. As mentioned above, this emphasizes the model decision regarding the cost-optimal amount of gas demand supplied and not supplied. Table 1 provides information for all model runs and associated scenarios related to the formulation/adaption of Equation 18, the obtained gas network design, and the individual results. Note that the cost-optimal gas demand supplied **(4^;™** m) without ensured supply (output of model run 1) is used as an input for model run 2 since it allows ~~by~~ the tailor-made adaption of Equation 18 to assess the shadow price A^C°y m for the cost-optimal gas network without ensured gas supply. Similarly, ~~the~~ model run 3 is used to obtain the shadow price f y m in case of cost-optimality with an ensured supply of the gas network.

3.4. Test-bed description

We illustrate the proposed model using the existing gas networks in ~~Vorarl-berg~~Vorarlberg, Austria~~, one of the nine Austrian provinces.~~. Reasons for this test field

	Input		Output
Model run	Formulation of Equation 18	Scenario description/gas network design (abbreviation)	Results or further used variable
1	qn,l,y,m ~~—~~ n,l,ym	Cost-optimal without ensured supply (CO)	Demand supplied (4^™^) Shadow price (A<C<°,y,m)
2	qdem _ __ _ 4 dem qn,l,y,m 4n,l,y,m		
3	qn,l,y,m n,l,ym	Cost-optimal with ensured supply (ES)	Shadow price (A^!Sl,y,m)

Table 1: Model runs and associated formulation of the gas demand constraint (Equation 18), scenarios, and results or further used variables.

include the fact that the gas networks there~~:~~ (i) are not connected to the rest of the Austrian gas network and can therefore be studied independently of it, (ii) include both high-~~pressure~~ and medium-pressure network levels that supply different energy services (e.g., heat for residential buildings, small and medium businesses~~,~~ (SMBs), and industry), and (iii) have ~~a~~ cross-border pipelines to Germany and Liechtenstein. Therefore, the investigation of the Vorarlberg gas networks in this work can be seen as a reasonable balance between complexity and simplification against the background of a newly developed and to~~-~~be~~-~~tested model.

3.4.1. Existing gas network in Vorarlberg, Austria

As mentioned above, the existing gas network in Vorarlberg, Austria, encompasses both a high-~~pressure~~ and a mid-pressure network. Particularly, the high-pressure network level includes a cross-border pipeline to Germany and Liecht~~-~~enstein. Table 2 provides a summary of Vorarlberg's gas network. The list of general indicators encompasses information related to the gas network, demand, and supply. Figure 2 shows the existing gas networks (left) and ~~its representa-tion~~their representation in the model (right) in Vorarlberg, Austria. ~~In particular~~Particularly, the high-pressure network level is comparatively well represented (difference of only 3 km or less than 4%). ~~However~~Nevertheless, the mid-pressure network level is ~~under represented~~underrepresented in the model. This issue is further processed in Sections 3.5, where we present the input data, and Section 3.6, where we discuss the limitations of the model. In ~~sum, Vorarl-berg's~~summary, Vorarlberg's gas networks are represented in the model by 36 nodes and 43 individual

List of general indicators	
Number of communities supplied	39
Number of end-user systems	32,615
Gas supply within Vorarlberg, Austrian	2098 GWh/year
Transmision to Liechtenstein	644 GWh/year
Number of green gas production facilities	2
Total green gas production	6.4MWh/year
Length of high-pressure network	83 km
Length of mid- and low-pressure network	2128 km

Table 2: Summary of Vorarlberg~~'~~'s gas network, demand, and supply in 2020. Source: [57].

pipelines.

3.4.2. Gas demand decline pathways at the community level until 2050 This section is dedicated to describ~~e~~ing the assumptions regarding the development of gas demands at the community level in Vorarlberg, Austria, until 2050. In a first step, we assess total gas demands at the community level in 2018 using information from the open ~~-~~data platform *energiemosaik* [58] and our own ~~data base~~database (see Section 3.7 for data availability). In a second step, we use the classification of communities regarding the energy demand provided by *energiemosaik* to estimate the composition of local gas demands. Accordingly, the local gas demand ~~at~~in the community is allocated to one or more of the following sectors of end-use or items: residential, agriculture, industry, and ~~small and medium business (SMB),~~SMB, service, and mobility. Building upon this characterization of gas demands by items, the following claim is made:

The composition of the local gas demand at the community level in 2018 determines its development until 2050. ~~In particular~~Particularly, each sector of end-use/item is associated with a decline pathway until 2050. Thus, the total gas demand at the community level until 2050 is described by a linear combination of the individual decline pathways per sector of end-use.

Table 3 shows the assumed annual decline rate (and thus decline pathway until

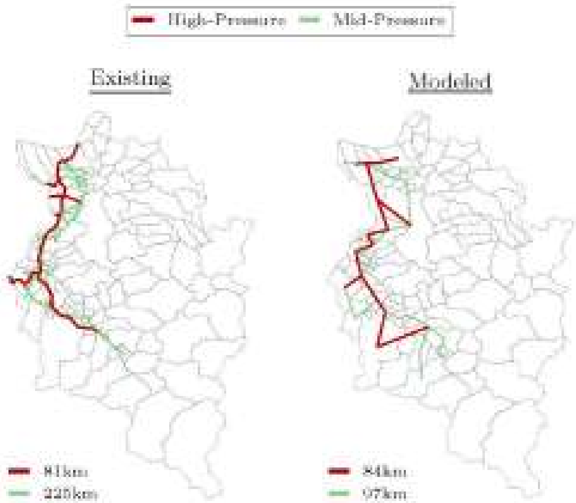


Figure 2: Existing gas networks (high-pressure in red and mid-pressure in green) in Vorarlberg, Austria (left), and its representation in the model (right). Source: [57].

2050) per sector of end-use. We use the naming convention from *energiemosaik* and use the names Type A, B, C, and D ~~to~~for a combination of different sectors of end-use. We restrict ourselves to four different types (A~~ to ~~–D) only. Note that 2050's share in gas demands are rough estimates including higher values if industry and SMBs are located there. For the residential/building heat demand, ~~linearly~~a linear decrease until 2040 is assumed.

Name	Residential	Industry	SMB	Service	Decline rate (2050's share)
Type A					~~l~~Linear~~ly~~ until 2040
Type B					~~l~~Linear~~ly~~ (15%)
Type C				/	~~l~~Linear~~ly~~ (20%)
Type D					~~l~~Linear~~ly~~ (35%)

Table 3: Annual decline rates for different compositions of gas demands at the local community level under the naming convention and sectors of end-use from *energiemosaik* [58].

3.5. Input data

This section shows a selection of the most relevant input data. At the same time, we refer to the authors~~'~~' GitHub repository (details in Section 3.7) for the complete input data. Table 4 shows the cost assumptions for gas networks including the specific investment costs ($c^{l}{}_{l}{}^{nv}$) and fixed costs per year (c^{fix}) for the different gas network levels. Note that 2030 is the assumed year of the ~~de-commissiong~~decommissiong and refurbishment investment decision for all pipelines within the networks. ~~In addition~~Additionally, the development of natural gas prices in Europe is taken from the World Energy Outlook 2021 [59]. The values from the so-called Stated Policies Scenario are taken: 26.28 EUR/MWh in 2030 and 28.33 EUR/MWh in 2050.[11] Revenues are generated in this work on the basis of gas network usage fees.~~ ~~Accordingly, we assume the following values for $pp^{o}{}_{y}$ for each year:

1 EUR/MWh (high-pressure) and 20 EUR/MWh (mid-pressure).~~[12]~~[13]

Type of costs	Symbol	Network level (l)	Value	Source
Specific investment costs (used in Equation 11)	c_{l}	Transmission High-~~P~~pressure Mid-~~P~~pressure	4600EUR/MW/km 4000EUR/MW/km 3000EUR/MW/km	[60] [61]
Fixed costs per year (used in Equation 5)	c^{fix}	Transmission High-~~P~~pressure Mid-~~P~~pressure	2000EUR/MW	[61]

Table 4: Cost assumptions of gas networks. The value of specific investment costs of the mid-pressure network level ~~are~~is scaled by the ratio between the existing and the modeled pipeline length (as shown in Figure 2).

3.6. Limitation of the model

Below, we discuss two different limitations of the model, whereas both can be associated with the trade-off decision between (spatial and temporal) granularity and computation time of the model.

[11]Assuming a linear development between 2030 and 2050.

~~[12] Note that the currently high natural gas prices are not explicitly considered. However, it can be argued that they are implicitly included as an additional driver for the assumed declining gas demand rates.~~

[13] Note that the currently high natural gas prices are not explicitly considered. However, it can be argued that they are implicitly included as an additional driver for the assumed declining gas demand rates.

3.6.1. Under-representation of mid-pressure networks and related pipelines With an eye on the representation of the mid-pressure gas network presented in Figure 2, it is evident that the corresponding pipelines of the mid-pressure network level are ~~under represented~~underrepresented in the model. The main reason for this is the (limited) spatial granularity at the community level since large parts of the mid-pressure network are within communities. Within the simplification of the geometry of gas pipelines to the spatial granularity on a community level, mid-pressure gas pipelines within a single community are not considered. This is why the introduction of a tailor-made scaling factor is needed ~~adjusting~~to adjust the specific refurbishment investment costs $(c_{mid\text{-}pressure})$ accordingly (see Table 4 in Section 3.5). Exemplarily, this scaling factor is ^l^{5}- (on average) in the case of the mid-pressure network level in Figure 2.

3.6.2. Resolution on a monthly basis and associated necessary scaling factors to calculate peak pipeline capacities

The temporal granularity of the model is limited since it generates results monthly within an individual year. Consequently, again, a scaling factor is needed~~ in order~~ to link the nodal gas balance constraints (monthly values) with the calculation of needed peak pipeline capacities (Equation 16). An hourly resolution could eliminate this calculation process, but, at the same time, one could run into serious computation time matters as the number of equations (i.e., gas balance constraints for node and network level) increases significantly.

3.7. Open-source environment and calculation time

The developed optimization model is implemented in Python 3.8.12 using the modeling framework Pyomo version 5.7.3 [62]. It is solved with the solver Gurobi version 9.0.3. For planning the development of gas networks in Vorarlberg, Austria, the model consists of 124155 equations and 98610 continuous variables. It takes on average 3 ~~seconds~~s to be solved using a computer with an Intel Core i7-8565U with 16 GB of RAM running Microsoft Windows 10 Pro with 64 bit. We use for data analysis the common data format template developed by the~~ Inte~~

Integrated Assessment Modeling Consortium ~~(IAMC)~~ using the open-source Python package pyam [63]. Note that all materials used in this study are disclosed as part of the publication ~~at~~on GitHub (https://github.com/sebastianzwickl). We refer to the repository for the codebase, data collection, and further information.

4. Results and discussion

This section presents the most relevant results of the analyzed test~~-~~ bed in ~~Vo-rarlberg~~Vorarlberg, Austria. Section 4.1 presents the cost-optimal gas network without an ensured supply (ES) of available gas demands (model run 1). Section 4.2 puts focus on the (nodal) shadow prices of the cost-optimal gas network without ES~~ensured supply~~ (model run 2). Especially, the latter highlights the impact of supplying additional gas demands at the LAU level on ~~the~~ network planning. Section 4.3 shows the cost-optimal gas network with ES~~ensured supply~~ (model run 3). Section 4.4 compares total costs and shadow prices ~~w/~~with ES~~ensured supply~~. This includes~~, among others,~~ the socialization of network costs until 2050. Finally, Section 4.5 shows the cost-optimal gas network without ES~~ensured supply~~ under the lumpiness of gas pipelines.

Comment [Editor3]: Remark: Please introduce LAU.

4.1. Cost-optimal gas network without an ES~~ensured supply~~ ~~ofgas~~of gas demands (CO)

In this case, the planning decision is made as follows: if the network operator can treat all energy services equally and thus can decide without restrictions if gas demands are supplied or not, then the gas networks will look like those presented here. Accordingly, it is assumed that competitive alternatives without dependence on gas networks exist for each energy service need. Figure 3 shows an overview of the most relevant results in this case. Figure 3 (a) shows the high- and mid-pressure gas networks. ~~In view of~~Given the existing gas networks (see Figure 2), it is evident that all high-pressure pipelines (in red) are refurbished. At the same time, 59~~-~~% of the length of mid-pressure pipelines are refurbished and 41~~-~~% are decommissioned. The maximum capacity of the high-pressure network level is

161.92~~ MW~~ and 40.58 MW of the mid-pressure (see Figure 3 (b)). Figure 3 (c) and (d) shows the development of gas demands supplied and not supplied for both pressure/network levels. ~~In particular~~Particularly, high shares of the mid-pressure demands are covered as a result of comparable high revenues at this pressure level. At the same time, no high-pressure gas demands are covered after 2030. Note that 2030 is the assumed year of the decommissiong and refurbishment investment decision for all pipelines within the networks.

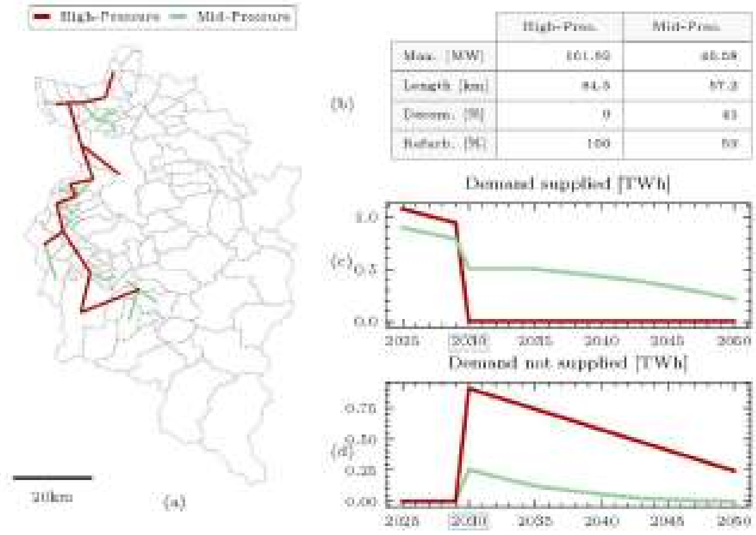
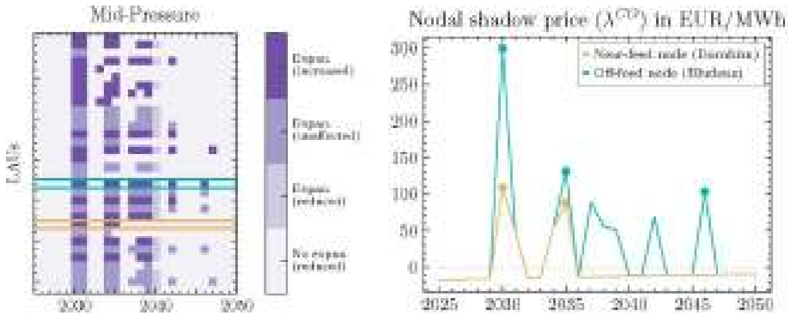


Figure 3: Cost-optimal gas networks without ensured supply (model run 1): (a) high- and mid-pressure pipelines, (b) overview of max pipeline capacity, length, and share of decommissioned and refurbished pipeline lengths, (c) demand supplied, and (d) demand not supplied at the high- and mid-pressure network level.

4.2. Shadow prices for supplying additional gas demands of the cost-optimal gas network without an ES~~ensured supply~~ ~~ofgas~~ of gas demands

This section takes the cost-optimal gas network without an ES~~ensured supply~~ of gas demands as a starting point and investigates the dual variables and shadow prices of the (nodal) gas balance constraints (see Section 3.3). In this case, emphasi~~zes~~s is put on the question: What costs arise and what network adaption is required if the network operator ~~needs~~is required to supply an additional gas demand at the nodal level~~, what costs arise and what adaption of the network is necessary.~~? Since the results of the previous section indicate that mid-pressure gas demands are supplied only (see particularly Figure 3 (c)), this section highlights (nodal) shadow prices of supplying additional gas demands at the mid-pressure network level. Figure 4 shows shadow prices for LAUs between 2025 and 2050. Figure 4 (a) shows the heatmap of the shadow prices, where the x-axis covers each year between 2025 and 2050 and the y-axis each node potentially connected to the mid-pressure network level. Thereby, each combination (i.e., node and year) is divided on the basis of four categories: (i) No expansion (reduced), which means that the network is able to supply the additional gas demand without expansion and thus the objective function value is reduced by the revenues for selling the additional gas demand at the mid-pressure network level~~,~~; (ii) ~~E~~expansion (reduced), which means that the network needs to be ~~extended in order~~extended to supply the additional gas demand but the objective function value ~~is still~~remains reduced but less than by the total revenues for selling gas demand at the mid-pressure network level~~,~~; (iii) ~~E~~expansion (unaffected), which means that the network ~~needs to~~must be extended and the objective value is unaffected and remains constant (i.e., shadow price equal to ~~zero~~0), and (iv) ~~Expansion (increased~~expansion (increased), which means that the network ~~needs to~~should be extended and the objective value would be increased (i.e., shadow price greater than ~~zero~~0). Figure 4 (b) presents the exact numbers of the shadow prices for two representative nodes, namely, a near-feed node (Dornbirn) and an off-feed node (Bludenz). Dornbirn is therefore ~~in the immediate vicinity of~~near the gas supply/source node, and Bludenz is further away from it. The shadow price at the off-feed node has several peaks (three are marked in 2030, 2035, and 2046~~)~~), and its maximum is 299.2 EUR/MWh in 2030. The near-feed node has two peaks (in 2030 and 2035) and its maximum is 109.0 EUR/MWh in 2030. ~~In particular~~Particularly, the development of the near-feed node after 2036 shows the capability ~~for~~of supplying additional gas demands since pipelines capacities are available without expansion.



(a) Heat map/capability of the network (b) Near-feed and off-feed node

Figure 4: Shadow prices for supplying additional gas demands at the mid-pressure network level: (a) heat map identifying the capability of the gas network to supply additional mid-pressure gas demands, and (b) temporal development of the shadow price for a near-feed node (Dornbirn) and a off-feed node (Bludenz).

4.3. Cost-optimal gas network with an ensured supply of gas demands (ES)

This section shows the results in the case that the network operator ~~needs to~~should cover all gas demands within the supply area. ~~In contrast~~Contrary to the previous two sections, no gas demands are not supplied. Figure 5 shows an overview of the most relevant results in this case.

Again, all high-pressure pipelines are refurbished~~,~~; however, 28% of mid-pressure pipeline lengths are decommissioned. The maximum capacity of the high-pressure network level is 465.06~~ MW~~ and 66.36 MW of the mid-pressure. Unsurprisingly, the objective function value increases significantly compared ~~to~~with the case without ES~~ensured supply~~. The objective function value increases by 96.29 MEUR. This value has great importance and implications for the practical planning of future gas networks. It can serve as a benchmark and is further investigated in the following section, which is dedicated to the comparison of the different cases.

4.4. Comparison of the cost-optimal gas network ~~w/~~with and without an ES~~ensured supply~~ of gas demands

This section compares the cost-optimal gas network with and without an ES~~ensured supply~~ of gas demands. We use the following abbreviations, as already used

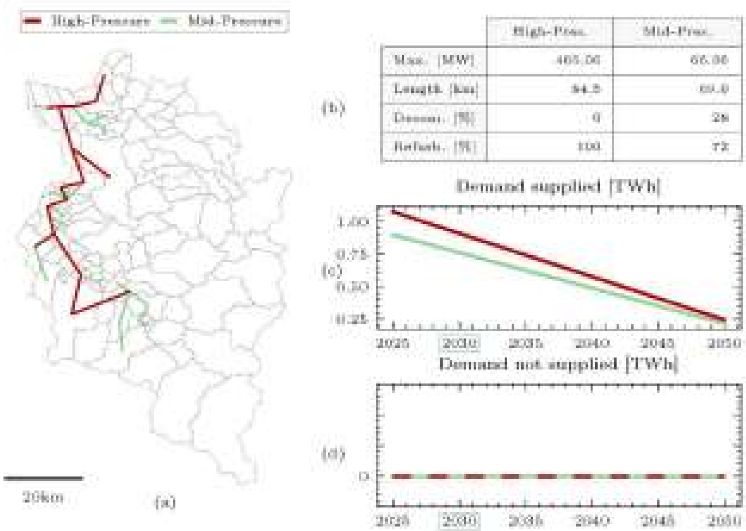


Figure 5: Cost-optimal gas networks with ensured supply (model run 3): (a) high- and mid-pressure pipelines, (b) overview of max pipeline capacity, length, and share of decommissioned and refurbished pipeline lengths, (c) demand supplied, and (d) demand not supplied at the high- and mid-pressure network level.

in Table 1: CO for the cost-optimal network without ensured supply and ES with ensured supply. We ~~put~~ emphasize ~~on~~ the difference in total costs for the network operator and the shadow prices. Figure 6 shows the most relevant results ~~in order~~ to compare the two cases, namely, the extra costs in the case of ES~~ensured supply~~ (see Figure 6 (a) ~~&~~and (b)), the distribution of 2030~~'~~s shadow prices (see Figure 6 (c)), and shadow price development between 2030 and 2050 for the near-feed and off-feed nodes.

As mentioned, the ES~~ensured supply~~ of all gas demands within the network results in extra costs of 96.29 MEUR. Given an equal~~ly~~ allocation to the LAUs and years, this results in extra costs of 107kEUR per LAU and year. This value ~~needs to~~must be ~~added~~considered as an additional offset to the shadow prices of the cost-optimal network with ES~~ensured supply in order~~ to obtain the effective shadow price and respect the already increasing total costs of the network operator. Nevertheless,

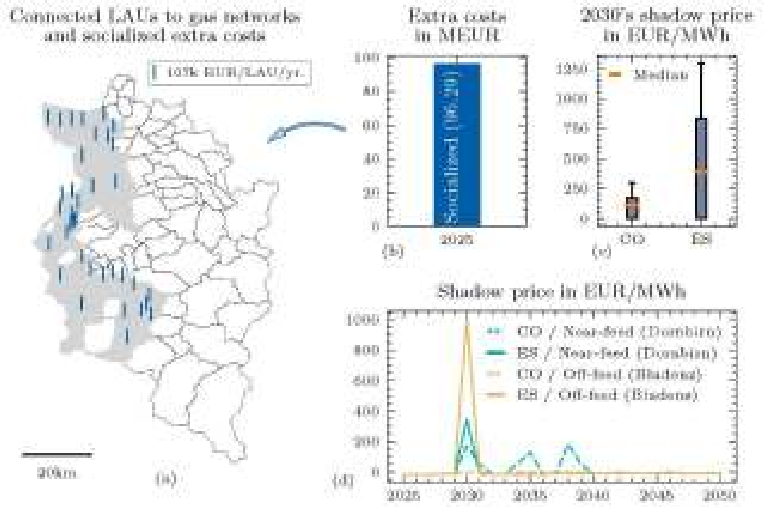


Figure 6: Comparison of the cost-optimal gas network w/ ensured supply of gas demands: (a) and (b) socialized extra costs, (c) 2030's shadow prices, and (d) shadow prices between 2025 and 2050 for the near-feed and off-feed node. CO: Cost-optimal without ensured supply; ES: Cost-optimal with ensured supply.

even the comparison of 2030's values without this offset shows that the shadow prices in the case with ES~~ensured supply~~ increase significantly compared ~~to~~with the case without ES~~ensured supply~~. ~~In particular~~Particularly, the median raises from ~~around~~approximately 100 ~~EUR/MWh~~ to 400 EUR/MWh. ~~In addition~~Additionally, the max value raises from ~~around~~approximately 300 ~~EUR/MWh~~ to 1300 EUR/MWh. This increase ~~of~~in shadow prices is also presented in Figure 6 (d), where again the near-feed and ~~an~~ off-feed nodes are shown.

4.5. Cost-optimal gas networks without ES~~ensured supply~~ under lumpiness of gas pipelines

This section shows the results of the cost-optimal gas network without ES~~ensured supply~~. ~~In contrast~~Contrary to the results presented above, we ~~take into account~~consider the lumpiness of gas pipelines in~~to~~ the network operator's planning decision. This analysis completes the results section against the background of two important aspects. First~~ly~~, considering the lumpiness of gas network pipelines increases the significance of the generated results for practical proposals since the network operator~~’~~'s decision is related to choosing specific diameters of gas pipelines. Second~~ly~~, however, the introduction of the lumpiness of gas pipelines extends the previous linear program to a mixed-integer linear program. This is why no dual variables and shadow prices can be obtained. Table B.1 in Appendix B shows the assumptions for the lumpiness of gas pipelines. We restrict ourselves to 14 different capacities (diameters between 0.1 and 1.3 ~~meter~~m) for both the mid- and high-pressure pressure/network levels. Figure 7 summarizes the results of the generated gas networks in case of lumpiness. Interestingly, the consideration of lumpiness of gas pipelines leads even in the cost-optimal case network without ES~~ensured supply~~ to the decommissioning of 23% high-pressure and 45% mid-pressure pipeline length. Furthermore, only gas demands at the mid-pressure network level are supplied (as in Section 4.1 and model run 1). Again, all the high-pressure gas demands are not supplied.

Figure 8 shows a comparison of the results under lumpiness with the previous results of the cost-optimal gas network ~~w/~~with ES~~ensured supply~~ (i.e., CO and ES). Particularly, it shows the impact of lumpiness on an optimal network design decision. In summary, the following interesting findings can be observed:

- The cost-optimal network design without ES~~ensured supply~~ under lumpiness of gas pipelines increases the total costs (i.e., objective function value) by only 1% (Figure 8, top left) but at the same time the amount of mid-pressure gas demand increases (Figure 8, bottom right~~)~~).
- Moreover, the lumpiness of gas pipelines results in both the decommissioning of high shares of the high-pressure network/pressure level (Figure 8, top right) and ~~a~~the further decrease~~e~~ing of the maximum pipeline capacity within the network (Figure 8, bottom left).

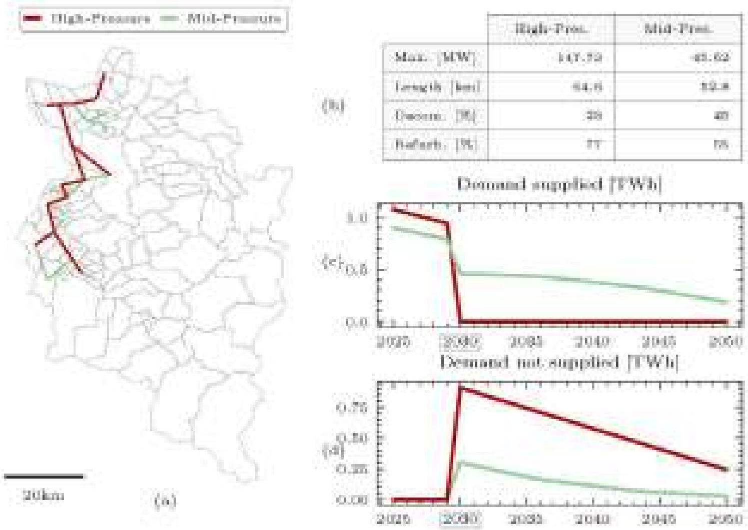


Figure 7: Cost-optimal gas networks with ensured supply under lumpiness of gas pipelines: (a) high- and mid-pressure pipelines, (b) overview of max pipeline capacity, length, and share of decommissioned and refurbished pipeline lengths, (c) demand supplied, and (d) demand not supplied at the high- and mid-pressure network level.

5. Conclusions and recommendations

The already ongoing defossilization of the provision of energy service needs leads to declining natural gas demands. Given that and under the expectation that green gases are very limited in ~~its~~their availability/potential, a transparent and critical discussion regarding the future development of gas networks without any taboos is needed. This also includes decommissioning of (parts of) the existing gas network infrastructure. This work investigates the trajectory of a gas network development within a test~~-~~bed until 2050. ~~In particular~~Particularly, the analysis is ~~carried out~~conducted from the network operator~~’~~'s perspective and shows different network decommissioning or refurbishment options under the decision of supplying or not supplying available gas demands.

We find that smaller gas networks (in terms of pipeline capacity and network

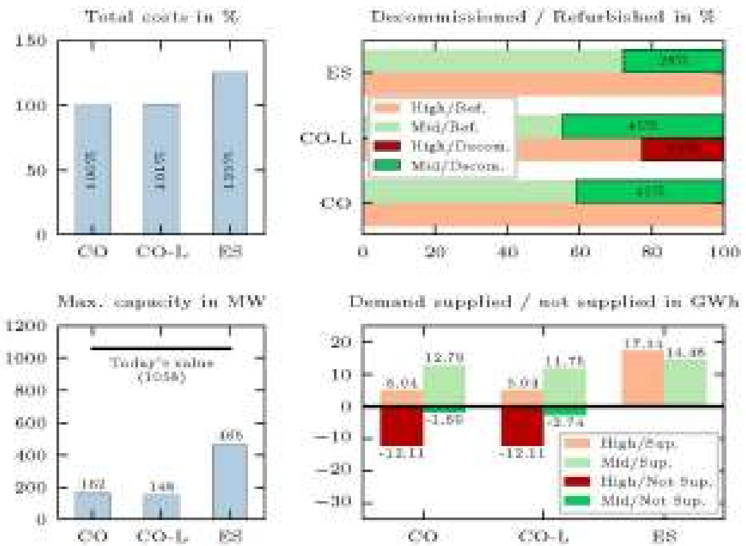


Figure 8: Results of the cost-optimal gas networks without ensured supply under lumpiness of gas pipelines (CO-L). Top left: Comparison of the total costs. Top right: Decommissioning and refurbishment decision at the mid- and high-pressure network level. Bottom left: Maximum pipeline capacity. Bottom right: Mid- and high-pressure gas demand that is supplied or not.

length) are needed in the future regardless of ES~~ensured supply~~ or not. However, the results indicate a wide range of possible network developments until 2050 resulting from the treatment of available gas demand. That reveals crucial trade-off decisions for gas network operators in the future and includes~~, among others,~~ the decommissioning decision of gas pipelines despite possible gas demand. Moreover, the conducted analysis of shadow prices of the local gas balance constraint shows that a balance/trade-off between the cost-optimal gas network design with and without ES~~ensured supply~~ could lead to a robust and economically competitive future of gas networks.

~~However~~Nevertheless, the results demonstrate that it is necessary to socialize network operators' costs under the remaining consumers connected to the network in the future. This fact has several important implications. First and foremost, that brings an additional cost component to consumers, which needs to be considered when dealing with the profitability of sustainable alternatives substituting natural gas. Analyses elaborating on trade-offs between natural gas and other sustainable supply options are often neglecting this network-related cost component, which brings a bias into the decision process.

Future work may investigate the development of gas demand ~~of~~ in different ~~sectors (~~sectors (e.g., building heat~~,~~ and industry~~, etc.)~~) in more detail. This could bring further insights into gas networks requirements and topologies until 2050. ~~Besides~~Additionally, the role/importance of green gases could be ~~improved. In particular~~enhanced. Particularly, further work should include different types of gas pipelines associated not only with the network/pressure level but rather with the quality of gas transported (i.e., share of hydrogen or synthetic gas).

Declaration of ~~interests~~competing interest

~~None.~~

~~Declaration of Competing Interest~~

The authors ~~report~~declare no ~~declarations~~conflicts of interest.

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Appendix A. Current natural gas demands in Vorarlberg, Austria

Figure A.1 shows current natural gas demands in Vorarlberg, Austria. The left subfigure shows natural gas demands in Vorarlberg, Austria, in 2018 and 2025. Open data and information from the internal ~~data base~~database [61] are used to split 2018's values into industry and (building) heating. The values are available at the provincial level (i.e., Vorarlberg, Austria). The 2025's values are calculated bottom-up. Th~~at~~is means that we use data ~~of~~on natural gas demands at the community level (between 2018 and 2025). Note that the difference between 2018's and 2025's gas demands reflects the lack of gas demand data at the community level only.

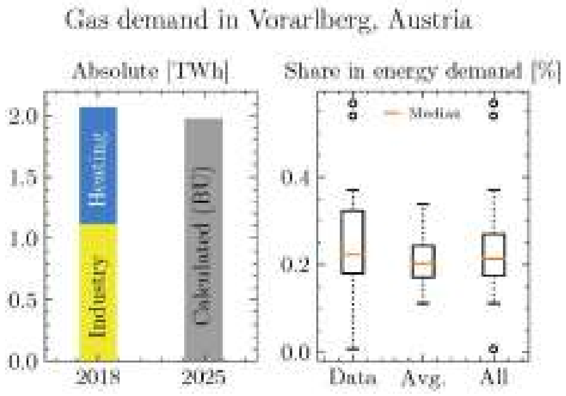

Figure A.1: Overview of gas demands in 2018 and 2025 (left) and share of natural gas in total energy demand (right). Data: open data available; Avg.: shares calculated based on the average gas demand per capita in Vorarlberg, Austria; All: Data and Avg. combined.

The right subfigure indicates the approach to calculating gas demands if no open data ~~is~~are available. It shows the share of natural gas demands in energy demand at the community level. The first item (Data) shows the distribution for those communities where data ~~is~~are available. The second item (Avg.) shows the distribution

~~bution~~ of gas demand shares using the average value of gas demand per capita in Vorarlberg, Austria. This calculation process based on the average gas demand is used for communities where no data ~~is~~are available. The third item (All) shows the distribution of gas demand shares for all communities.

Appendix B. Assumptions regarding lumpiness of gas pipelines

Similar to [64], we assume a simplified relationship between the diameter of gas pipelines and their capacities. Accordingly, we assume that the capacity of high- and mid-pressure gas pipelines increases by 2.5 times the power of the diameter. Table B.1 summarizes the set of potential diameters and the corresponding calculated capacity.

Diameter in meters	Pipeline capacity in MW
0.1	0.82
0.2	4.62
0.3	12.72
0.4	26.11
0.5	45.62
0.6	71.96
0.7	105.8
0.8	147.73
0.9	198.31
1.0	258.07
1.1	327.51
1.15	366.0
1.2	407.09
1.3	497.27

Table B.1: Set of diameters of gas pipelines and assumed pipeline capacity.