HOW CAN THE GAS SECTOR CONTRIBUTE TO A CLIMATE-NEUTRAL EUROPEAN ENERGY SYSTEM? A QUALITATIVE APPROACH.

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Abstract

Background: Mitigating climate change requires fundamentally redesigned energy systems where renewable energy sources replace fossil fuels such as natural gas by 2050. Just how exactly this renewable energy will be transported to end users and how supply and demand will be balanced are still subject to lively debate. In this context the gas sector underlines its capability to contribute and claims its role in the EU energy system beyond the age of the fossil fuel natural gas. But on which specific arguments is this claim based and which enabling factors need to be considered?

Methods: We take a two-step approach: We begin with a theoretically guided review of studies from energy industry and academic sources to discuss pros and cons from a holistic energy system design point of view. We then enrich our review with the results of an empirical focus group process, which leads us to possible enabling factors for unlocking the contributions of the gas sector to a climate-neutral energy system exemplified for Austria.

Results: Beyond the widely acknowledged potential of the gas infrastructure for balancing growing renewable electricity generation and demand, we find that renewable gas could be a means to transport renewable energy to end users, and that it could be done using existing infrastructure. This could reduce the costs for society, increase public acceptance and ultimately speed up the transition to a climate-neutral energy system. However, this hinges on a supportive regulatory framework for energy markets and usage and on optimized resource utilization across the society as enabling factors.

Conclusion: Developing a climate-neutral EU energy system will mean investing large amounts of money and completely overhauling our current system. The entire energy supply chain across various energy vectors must be optimized. This will require a technology-neutral and holistic approach. The regulatory framework must provide investment conditions that respect these principles. If it does, renewable gases could make a valuable contribution to achieving climate goals in an efficient, timely and publicly acceptable manner.

Keywords: climate neutrality, renewable gases, renewable hydrogen, renewable methane, biomethane, power-to-gas, energy transition, energy system, energy policy

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1. Background

Europe's gas sector currently covers between 20 and 25% of European final energy demand overall [2]; its powerful high-pressure network has a length of 240,000 km [3]. But at first sight, the future of this potent industry sector seems dire: The climate-neutral energy system of the future appears to have no room for an entire sector that is traditionally oriented towards the fossil fuel natural gas. But the players in this industry sector are increasingly vocal in countering such premature conclusions; they seek to actively define the role it can play in the future. This is also acknowledged by authorities such as the European Commission and the Council of European Energy Regulators, which gradually concede that the gas sector may have a sustainable future beyond fossil fuels, beyond natural gas. The organizations and assets of the gas sector, such as its extensive network, could facilitate the transition to a climate-neutral European energy system and be a long-term element of it.

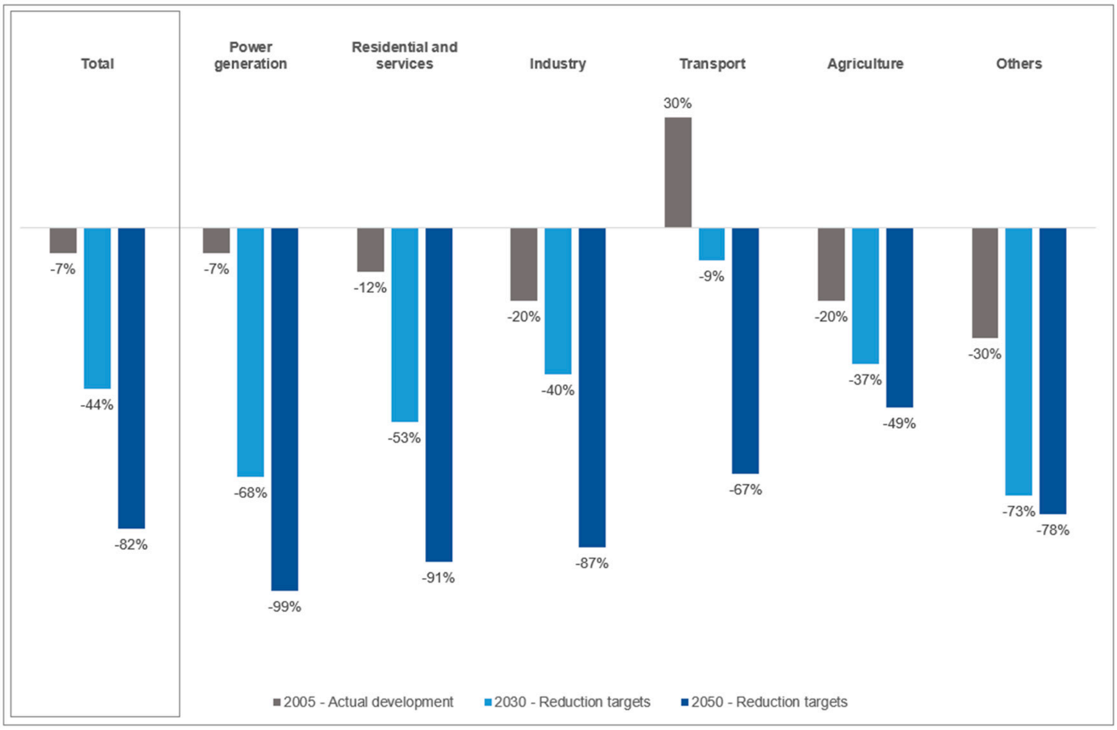
So far, relevant research has focused on different technological options and the commercial viability of specific cases in particular regions. In this paper, we build on a qualitative research strategy to develop an idea of the role that the gas sector could play in a climate-neutral future EU energy system. Applying, for the first time, a holistic approach to the matter enables us to contribute to closing three major research gaps: (i) the specific functions of the gas sector and renewable gases in a future EU energy system's supply chain (ii) the major societal implications of such gas sector contributions to a future EU energy system, and (iii) the implications that a future EU energy system which includes the gas sector has for policy making.

Specifically, this paper is the first theoretically guided compendium of the main arguments in favor and against the gas sector playing a role in the future EU energy system (research question 1). This is based on a review of studies and analyses done by energy industry organizations and academia. The consolidated findings of this review are enriched by the empirical results of a focus group process with Austrian gas sector experts which took place in the context of the development of the Austrian government's climate and energy strategy for the period until 2030. This process also provided conclusions about the enabling factors in energy policy, energy regulation and beyond which are needed for the gas sector to be able to deliver on its potential (research question 2).

1.1. Commitment to establish climate neutrality as a trigger for changing the EU energy system

If industrial countries are to meet the objectives of the Paris Agreement, they will need to reduce their greenhouse gas emissions (GHGE) by at least 80% compared to the 1990 benchmark by 2050 [7]. Simply spoken, this means cutting GHGE by half in each decade to come [10]. With this in mind, the European Union has set sector-specific reduction targets and pathways (see Figure 1).

Figure 1: Sector-specific reduction targets and pathways; modified, after [12].



It is evident from Figure 1 that the energy end-use sectors such as power generation, residential/services, industry and transport account for the lion's share of GHGE at the moment. They will thus have to realize substantial reductions by 2050 [12]. And given the fact that this EU target was formalized prior to the Paris Agreement, we can consider it to be the absolute minimum effort to be undertaken [13].

For energy end use sectors there are at least technological concepts for realizing such a radical change with a limited need for behavioral changes, i.e. they are socially acceptable. Other sectors, such as agriculture, are not in this position [12, 14]. This fosters a widespread expectation within the energy industry, academia and among policy makers, namely that the end use of energy will have to be virtually climate neutral by 2050. Such a net zero balance of associated GHGE can be realized by (i) avoiding emissions by replacing fossil fuels with renewable alternatives, (ii) eliminating emission of the predominant greenhouse gas by utilizing carbon dioxide in closed-loop industrial processes, and (iii) sequestering carbon dioxide for permanent storage in geological underground formations.[a]

1.2. Overall objectives for and way forward to a future EU energy system

Looking at GHGE reduction targets in isolation when defining measures to reconceptualize the energy system is insufficient. EU energy policy is based on the threefold aim of creating a sustainable, secure and competitive system [1]. Consequently, climate neutrality may act as the immediate trigger for change, but the transition to and the maintenance of a sustainable future energy system must also provide for a maximum of cost-effectiveness to ensure the affordability of energy for European consumers and the competitiveness of European businesses on the global market [15]. In this line of thinking, the notion of competitiveness is closely linked to sustainability: only a cost-effective and thus competitive system will be able to attract the level of public acceptance required for such a material long-term change. The same applies for security of supply. Based on these fundamental objectives, there is broad consensus within European Union policy circles on a number of characteristics of the future EU energy system.

Firstly, energy efficiency will be a pillar of the system. All sectors must undertake substantial efforts to increase energy efficiency [1, 16]; this translates into the policy objective of reducing final energy demand by 20% by 2020 [17], and by 30% by 2030 [18].

Secondly, fossil fuels as primary energy source are not compatible with a climate-neutral energy system. Though natural gas can be a bridge fuel with comparatively little climate impact, the GHGE reduction targets can only be reached if we abandon, by 2050, all significant use of fossil fuels. This includes natural gas.

Thirdly, primary energy needs to be provided from renewable energy sources (RES). The last decade has already seen substantial steps towards positioning renewable generation as centerpiece of the energy system. The share of renewable generation capacity in Europe has increased from 11% to 18% over the last eight years [19], and growth can be expected to continue dynamically.[b]

Beyond these basic features, the concrete way forward for achieving the policy goals and implementing changes to the energy system design is substantially less clear.

A comprehensive 2016 Delphi survey of 450 experts about the future EU energy system formulated the hypothesis of an "all-electric society" with electricity as single energy vector to emerge in the long run [20]. A discussion at the 30th meeting of the European Commission's Gas Regulatory Forum (Madrid Forum) in October 2017 arrived at a different conclusion: The published minutes show that participants expect a dual energy system for the future, with a significant role of renewable gas alongside renewable electricity. They also stressed the need to implement cost-efficient measures, taking into account the value of the existing gas infrastructure [21].

A study by the Council of European Energy Regulators (CEER) about the future role of gas from a regulatory perspective follows the same lines of thinking: In the interest of EU energy consumers and of a cost-effective transition to a future energy system, the EU must make best use of the potentials of the gas sector. These include a finely meshed network that connects 118 million end users within the Union [22], comprehensive storage infrastructure, and the potential to substitute natural with renewable gas [15]. But again, specific measures for how to realize this objective are not yet sufficiently agreed or even defined.

2. Methods

In this paper, we apply a qualitative strategy to answer the research questions. To address research question 1, we conducted a literature review of studies and analyses about the role of the gas sector in the energy transition. More specifically, we analyzed a sample of recently published papers to identify arguments in favor and against the potential contributions and functions of the gas sector. We used the following criteria to select the papers for our sample: (i) qualitative and/or quantitative assessment of renewable gases as part of an energy system; (ii) application of a climate scenario that requires a GHGE reduction of at least 80%; (iii) geographic scope of at least one EU member state or the entire EU; (iv) consideration of at least one energy end use sector; and (v) publication during the last 3 years. This resulted in a sample of eight studies (see Table 1).

Table 1: Sample of studies reviewed [4, 6, 9, 13, 23–26]

Title	Author	Year	Geographic scope	Method	Sector(s) covered	Main conclusions	Ref.
Gas for Climate – How gas can help to achieve the Paris Agreement in an affordable way	van Melle, T. et al.	2018	EU	Qualitative + quantitative	Buildings, electricity, industry, heavy duty transport	- Renewable gas generation capacity in the EU can reach a significant level by 2050. - A future energy system including this renewable gas shows substantial cost savings compared to a system without renewable gas.	[13]
Energiemarkt 2030 und 2050 – Der Beitrag von Gas- und Wärme-infrastruktur zu einer effizienten CO2-Minderung	Hecking, H. et al.	2017	Germany	Qualitative + quantitative	Heat, electricity, industry, transport	- A future energy system which still comprises gas and heat infrastructure shows substantial cost savings compared to a system focused on electrification and allows adjusting to technological developments more flexibly. - A significant part of the renewable gas required for such an energy system design will be imported from outside the EU.	[23]
Der Wert der Gasinfrastruktur für die Energiewende in Deutschland – Eine modellbasierte Analyse	Bothe, D. et al.	2017	Germany	Qualitative + quantitative	Buildings, industry, transport	- A future energy system with volatile renewables as predominant energy source relies heavily on gas storage to balance supply and demand. - The additional use of the gas infrastructure to transport renewable energy in gaseous form to end users shows major benefits and cost savings compared to an electricity-focused system.	[9]
Green Gas Potential in ONTRAS Network Area	nymoen|strategie-beratung	2017	Germany (regional)	Qualitative + quantitative	Buildings, electricity, industry, transport	- A future energy system design strongly based on synthetic methane produced from wind energy via power-to-gas shows costs similar to a system design oriented towards electrification. - Beyond that, the gas-based design scenario shows various cost upsides and qualitative benefits.	[4]
Riesiges Potential an grünem Gas	Papp, E. J. et al.	2017	Austria	Qualitative + quantitative	Residential	- Renewable gas generation capacity in Austria (predominantly for biomethane) can be expanded to a level that allows complete substitution of natural gas in the residential sector by 2050. - This avoids stranding of gas assets and ensures end-user gas prices that remain competitive with alternative heating technologies while being fully climate-neutral.	[24]
Kalte Dunkelflaute – Robustheit des Stromsystems bei Extremwetter	Huneke F.; Perez Linkenheil C.; Niggemeier M.	2017	Germany	Qualitative + quantitative	Electricity	- Gas storage can be combined with power-to-gas to provide an energy system with high security of supply even in extreme situations, while the costs for society would remain adequate.	[25]
Klimaschutz durch Sektorkopplung - Optionen, Szenarien, Kosten	Ecke, J. et al.	2017	Germany	Qualitative + quantitative	Heat, electricity	- The transition to a future energy system should take a technology-neutral approach to limit lock-in effects. - The gas sector has the potential to contribute as a major flexibility source and to enable cost savings compared to an energy system design without renewable gas and gas infrastructure.	[26]
Erneuerbare Gase – Ein Systemupdate der Energiewende	Klein, S. et al.	2017	Germany	Qualitative + quantitative	Heat, industry, feedstock, transport, electricity	- The achievement of 2050 climate targets is only possible with a future energy system design that includes the gas infrastructure and a significant level of renewable gas (>900 TWh/a). - This will also realize substantial cost savings compared to a scenario without a significant role of the gas sector.	[6]

Most of the studies in the sample (see Table 1) focus on Germany, where the extensive “Energiewende” debate has created substantial attention for energy system design issues. Even so, we can assume that the results are generally valid given the large extent to which German energy policy making is predefined at EU level and the representative share of gas in the German energy mix [2].

Publications in academic journals that would be relevant for the present paper have been few and far between;[c] to ensure that we take a comprehensive and up-to-date view of the current discussion, the sample mostly includes studies from academic institutions, consultancies, etc. In addition, we used relevant findings from academic articles that cover specific aspects to enrich our review (see Table 2).

Table 2: Articles about specific aspects used to enrich the review sample

Aspect	References
Energy storage technologies and potentials	[27–29]
Renewable gas production technology	[30–34]
Renewable gas production costs	[35]
Hydrogen as an energy vector	[36–38]
Legal/regulatory background	[39–42]
Others	[43–45]

After the literature review, we addressed research question 2, about the enabling factors for the gas sector contributions previously identified. For this, we focused on Austria and based our work on the results and experience gained during a project carried out by the Energy Institute for the Austrian Association of Gas- and District Heating Companies. It was the objective of this project to come up with a position that could serve for them to input to the update of the national climate and energy strategy of the Austrian government. The finalized climate and energy strategy was published in June 2018 [46].

The Energy Institute set up a series of discussions with experts from the Austrian gas sector and social partners involved in energy policy making.

Table 3: Details of focus group sessions of held by Energy Institute at the Johannes Kepler University Linz for the Austrian Association of Gas- and District Heating Companies

Date	Number of participants	Participation of social partners
Oct. 2017	6	no
Dec. 2017	17	yes
Feb. 2018	15	yes
Apr. 2018	16	yes

Bringing in the social partners enriched the internal perspective of gas sector companies with expertise about the impact of energy strategies on society as a whole, without particular focus on the gas sector. The four discussion sessions that took place (see Table 3 for details) were prepared by the Energy Institute at the Johannes Kepler University Linz and moderated by Mr Horst Steinmüller in his function as head of the institute.

For the present paper, we performed a thematic analysis of the records of these discussions and of documents prepared on the basis of discussion results.

3. Results and discussion

The results of applying the above methodology are presented below. We start out with our results on the potential contributions of the gas sector to a future EU energy system and its functions therein (research question 1). We then move on to the enabling factors for these contributions (research question 2). In the end, we provide an overview and discussion of our main results.

3.1. Potential contributions of the gas sector to a future EU energy system

Research question 1 deals with the ways in which the gas sector can contribute to a climate-neutral future energy system. The results are separated into arguments in favor and arguments against such potential contributions.

3.1.1. Arguments in favor of potential gas sector contributions

Gas can serve as seasonal storage of renewable energy: The electricity system requires a constant balance between generation and demand; there is very little potential for storing electricity on the network. As both the share of intermittent RES (such as wind and solar) and overall electricity demand increase,[d] this limited electricity system flexibility becomes an issue [13]. At the moment, it is fossil fuels that provide substantial system flexibility, but they will need to be replaced in the long run due to the emissions they cause.

Often, pumped hydroelectric storage is hailed as climate-neutral solution to the flexibility issue, but its potential is limited. At the moment, pumped hydroelectric storage capacity in the EU amounts to 40 TWh, which equals the average EU electricity demand over five days. Even the absolute maximum theoretical potential of pumped storage capacity is no more than 123 TWh [27].

Battery solutions for storing electricity are another option, but even though their efficiency increases and their cost declines rapidly, they will not reach competitive investment cost levels by 2050 [13]. And even if they do, their self-discharge characteristics limit their potential for seasonal storage [6, 13].

Storing energy in the form of gaseous fuels, on the contrary, is an established gas sector practice for short-term and, particularly, seasonal balancing needs. Existing gas storage infrastructure could be used to cover at least the seasonal storage demand that arises from the growing amounts of energy from renewable sources on the network [28, 29, 37].[e]

Beyond dedicated storage facilities, also the gas and electricity networks itself have different storage-related characteristics. The gas network disposes of large volumes of linepack and can manage substantial pressure differences. It is thus much easier to balance and bears a lower risk of end-user supply disruptions [39].

Gas networks can reduce the need for electricity network expansion: Recent electricity network expansion plans have faced difficulties and involve large investments; adapting the network to RES as a major generation technology and to increased electricity demand will require further expansions at substantially larger scales.

Therefore, it appears rational to maximize use of any existing energy transport infrastructure, including the one for gas.

Both European policy makers and regulators widely support the view that strain on the electricity network could be relieved by transporting renewable energy to end use destinations through the gas network [4, 9, 13, 37]. Some studies even consider this to be the gas sector's main contribution to societal cost savings in the transition to the future energy system [6, 13, 23].

Replacing natural gas by renewable gas enables climate-neutral energy end use: The gas sector acknowledges the need to reduce GHGEs. At the same time, representatives underline that the technological solutions to replace natural gas with renewable gases are already in place. These gases would only create such an amount of GHGE which has been captured during their production and thus allow that all gas consumed in the EU will be climate-neutral by 2050 [6, 13].

Basically, renewable gases are produced either by turning biomass into biomethane or synthetically, by way of power-to-gas. This latter technology uses water electrolysis to convert RES electricity first into renewable hydrogen and then, possibly, into renewable methane.[f] The detailed technical characteristics of these technologies are beyond the scope of this paper, but we refer the interested reader to the papers of Wall et al., Schaaf et al., Bagi et al. and Götz et al., which provide reviews of research related to renewable gas production with a technology focus [30, 32, 47]. For this paper, we focus on the characteristics of these technologies from an energy system design point of view.

While the use of biomethane is limited by the availability of biomass resources [13], its long-term potential is often underestimated. Both policy makers and researchers rank the objective to create a circular economy highly. Such a circular economy implies extensive, cascading use of resources; maximum value is to be extracted during usage, and residues are used for energy generation in a last step, but at a maximum level [30, 43]. The European Commission has translated this vision into a zero waste program for Europe [40]. The estimations of biomethane potentials that are currently used are based on a mindset which is not sufficiently coherent with these principles and thus have a substantial upwards potential.

The analyzed studies discuss several benefits related to the use of biomethane. In particular, they point out that biomass can be easily stored, which allows for optimized generation that contributes to system flexibility and, thus, security of supply [13]. The latter is further reinforced as expectations for decentralized, local biomethane production could translate into reduced dependence on energy imports. This would also create new jobs and strengthen the rural economy [13, 30].

As already mentioned, renewable gases can be of biogenic origin but can also be produced synthetically, through power-to-gas. This is particularly relevant for unlocking the potential of the gas infrastructure to store and transport electricity produced from RES. It not only enables using excess RES generation instead of curtailing it [4] but also unlocks roles for the gas infrastructure beyond pure storage. Hydrogen and renewable methane could become “energy vectors” to meet any final energy need in a climate-neutral way [36].

The potential to blend hydrogen into the existing natural gas system is limited to single-digit percentage shares. Higher percentages might require some adaptation of network infrastructure and end-use appliances [13, 38].

This is not the case for renewable methane. While its production, through methanation of renewable hydrogen, implies additional investments and conversion losses, it delivers a range of benefits: From a chemical point of view, it is almost identical to natural gas and thus requires no adaptation of network infrastructure or end-use appliances. Also, it can utilize carbon dioxide emissions from combustion processes or biomethane production in circular processes or reduce the amount of carbon dioxide in the atmosphere through direct air capturing [9, 13, 24, 33, 34].

Beyond the intra-EU potential for the production of renewable gas, there is the possibility to import renewable gases [9, 13, 35]. The study by van Melle et al. looks at Ukraine and Belarus, which are close to EU markets and well connected through existing pipelines. It finds that these two countries alone could provide an additional 20% on top of the intra-EU production potential [13]. Hecking et al. and Bothe, D. et al. also refer to the comparative cost advantages of production regions outside the EU and expect major imports in the long run [9, 23, 23].

Irrespective of the specific origin of gas, it can be used to meet various final energy needs [37]. While the extent to which renewable gases offer advantages over alternatives differs between sectors, there are potentials in all end-use sectors.

Transport

Most of the studies we analyzed assume that individual transport will see significant levels of electric vehicles in the long run [6, 13]. This assumption, however, is mainly based on the policy perspective and does not include the economic considerations of end users or qualitative issues that influence the purchasing decisions of end users, such as insufficient charging infrastructure, reduced ranges and significant charging times [6].

Even though there is little use of gas in the transport sector at the moment,[9] renewable gas (including hydrogen to feed fuel cells) could be an alternative or supplement to liquid biofuels and help reduce transport-related GHGE [37]. This is particularly relevant in heavy-duty road transport, where electric drives face technological limits [13].

The European Union recognized this important contribution that renewable gases could provide with Directive 2014/94/EU. This Directive stipulates that the maximum distance between refueling points for compressed natural gas should not exceed approximately 150 km, and that between liquefied natural gas refueling stations 400 km [41].

Beyond road transport, there is the even more complex challenge of reducing GHGE in the aviation and maritime sector. For aviation there is a technological need to use liquid biofuels, as neither electrification nor the use of

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gaseous fuels is possible [6, 9]. The maritime sector, however, could use renewable gases, given their cost advantages compared to synthetic liquid biofuels [6].

Buildings

Heating systems of residential buildings involve considerable financial and practical considerations and there is a variety of technological solutions that compete with each other in this sector. Also, the buildings sector within the EU is considered to be highly important when it comes to assessing the potential role of the gas in the future [13].

The sector is currently based on fossil fuels to a substantial extent, and usually, it is direct electrical heating, renewable central heating, and especially electric heat pumps driven by renewable electricity that are discussed as a way to reduce its GHGE. Even so, the studies we analyzed argue that renewable gas can make a beneficial contribution to a future energy system in this sector also [9, 13, 23, 24]. Proponents argue that using existing network and storage infrastructure would create added value also for end users and therefore for society as a whole. These arguments are addressed in detail later in this paper. Beyond the question of whether natural gas is replaced by electric forms of heating, there is a consideration that relates to the existing building stock. Renewable gases could replace other fuels that have similar heating system characteristics but substantially different GHGE; in particular, renewable gases could actively contribute to GHGE reductions by replacing oil as a heating fuel. This would deliver “quicks wins” in reducing GHGE [3, 28].

Industry

While electricity can be an energy source for various low and medium temperature industrial processes, there are technological limitations with regards to high temperature needs [13, 23].

The European steel-making industry, one of the major gas consumers, is e.g. exploring ways to electrify energy-intensive processes by using, among others, electric arc furnaces instead of traditional blast furnaces. Such research and development could lead to electrification’s technical limitations being overcome over time [44]. Nonetheless, the decisive question will be how this would affect the competitiveness of the European industry on the global market.

In addition to the energetic use of natural gas in the industry, Klein et al. particularly consider the non-energetic use of natural gas, i.e. gas as a material resource, in industrial processes. They outline that, based on existing technologies, a renewable gas volume of 280 TWh/a would be sufficient to replace current fossil feedstock use in Germany and to achieve climate-neutrality in this respect [6].

Electricity generation

Considering the ambitions to fade out coal-based generation capacity in the medium term, gas-fired generation could be a logical source of system flexibility that would help balance a RES-dominated electricity system. In a largely climate-neutral energy system, however, the fuel used will have to be biomethane or be based on the power-to-gas-to-power cycle, which requires multiple conversions but is considered a competitive avenue especially for addressing seasonal storage needs [26].

Utilization of readily available gas infrastructure requires little investment: Given the fact that the natural gas infrastructure is already in place and capable of transporting and accommodating even larger volumes than in recent years, deployment of renewable gases can be expected to require no large-scale network expansion. Necessary investments would be limited to connecting a significant number of biomethane generation plants and power-to-gas facilities [13]. Another advantage of the European gas network and its major transit pipelines is the high level of interconnectivity between member states. This could facilitate widespread use of renewable gas within the Union while maintaining a high level of security of supply. Moreover, it provides efficient access to different potential production sources of renewable gas across Union borders [9].

Of course, operating the gas network will cause operational costs for network maintenance [13], but this could also be expected of an expanded electricity network.

A further consideration raised in the studies we analyzed is that gas pipelines which are not used anymore might need to be removed from the ground [9]. If a future energy system indeed considers gas infrastructure to be redundant, such removal could cause significant societal costs.[h]

Hecking et al. call for a differentiated view of this issue. While comprehensive electrification of energy end use could indeed lead to a need to dismantle gas distribution infrastructure in the long run, the significance of gas-fired power plants would require the gas transmission infrastructure to remain in place or even be expanded. This is problematic insofar as this high level of capacity would be used to provide flexibility, i.e. it would be operated during few hours only. This would in turn negatively impact network tariffs and investment attractiveness [23].

Using renewable gas as part of the future energy system can contribute to the economic sustainability of the existing gas infrastructure, which is subject to an extensive cost regulation regime. It could prevent investments from being stranded [24] and avoid the related detrimental societal cost effects.

The gas sector can speed up the transition to a future energy system: The studies we analyzed argue that a combination of increasing renewable electricity generation and a well-defined involvement of the gas sector can speed up the transition to a climate-neutral energy system [13]. Looking at renovation rates, which are currently particularly low,[i] even just insulating residential buildings to the degree required for a transition to electric heat pumps would take decades. The same is assumed for central heat networks in buildings on a large scale [13]. If end users continue using gas-fired appliances based on renewable gas, this could significantly speed up the transition [23].

A gas sector contribution to a future energy system can mitigate public acceptance issues: We can assume that renewable energy sources such as wind or solar are nearly inexhaustible. However, local resistance to large-scale generation capacity construction may also be substantial. Also, the overhead lines common in electricity transmission networks are often perceived negatively by the affected local communities [13]. Public acceptance is less of an issue for gas networks, because they are mostly underground [9]. And there is another aspect which is not yet in the focus of the public debate but needs to be considered in this context: An electricity-dominated energy market design will create the need for substantial expansions of the electricity distribution network [9].[j] This contrasts with the gas infrastructure, which is already in place; major construction works, and negative effects for the public, are not expected.

Beyond infrastructure projects, acceptance must also be considered for activities that would be required on the end-user side, such as replacing heating systems and/or insulating buildings. These activities and the related costs are not only a social factor; they can also be expected to be decisive for the long-term sustainability of policy objectives and measures to actually operationalize the climate targets [9].

A gas sector contribution to a future energy system can foster security of supply: Gas meets with higher public acceptance and requires fewer large-scale network investments than electricity to be able to accommodate RES as a dominant source of supply. Due to these characteristics, renewable gases can be particularly valuable when it comes to maintaining a high level of security of supply [4, 9]. Also, an energy system with multiple energy vectors is less concentrated and therefore more flexible in stress situation [4, 23, 23].

A gas sector contribution to a future energy system can ensure cost effectiveness from a societal perspective: Even if we disregard that the generation costs for renewable gases are expected to fall due to technological improvements, scale-up of average plant size and economies of scale [13, 35], the mere generation costs of renewable gases lie well above those of natural gas [37].

This is particularly true for power-to-gas, whose conversion losses make the process sensitive to the cost of electricity as an input to the conversion. However, if excess RES generation with low alternative value is used for the electrolysis, the value added by power-to-gas conversion is particularly high [13]. On the other hand, the related investment costs are substantial and thus require sufficient operating hours. An optimal range is 3000-6000 hours per year; fewer than 2000 hours of operation per year typically render conversion assets uneconomical [36].

Beyond the mere generation costs of renewable gases, the studies we analyzed demand a holistic view of the energy system cost that results from the system's overall architecture and from the role it attributes to the gas infrastructure and renewable gases. All arguments in favor and against the potential role of the gas infrastructure and renewable gases need to be factored in when modeling societal cost implications; this should then be the basis for policy making.

We recognize that the analyzed studies have limited comparability in terms of the scenarios and end-use sectors considered, the assumptions, the geographical scope, the assessment methodology, etc. However, they all model the societal cost implications of an energy system that includes renewable gases compared to an alternative system design with electrification of major parts of the energy supply chain.

Examining these results in an integrative way shows that gas sector contributions can have substantial societal cost benefits and underlines the potential of gas. Interestingly, the studies arrive at this same conclusion even though they assume substantially different settings for renewable gas production.

One group of studies researches the impact of renewable gases based on the assumptions that power-to-gas is applied for domestic RES excess generation only and that advanced or even extensive volumes of biomethane are produced domestically. According to van Melle et al., who take the EU as geographic scope, this can create societal cost savings of EUR 138 billion per year by 2050; these are mainly generated as investments towards adapting residential heating concepts and expanding RES generation capacity and electricity networks become redundant [13]. Bothe, D. et al. and Ecke et al. provide a similar argument, estimating societal cost savings in Germany at EUR 12 billion [9] respectively EUR 4 billion per year [26] by 2050. Also Huneke et al., with their focus on the interrelation between flexibility/storage options and the demand for RES generation capacity, postulate that the use of power-to-gas in combination with seasonal gas storage can provide an energy system with high security of supply at adequate societal costs, even in extreme situations [25].

Another group of studies does not limit power-to-gas to excess RES but considers RES generation capacity and the related use of power-to-gas as an endogenous result of overall energy system optimization. They expect the additional investments in RES generation capacity and the transformation losses from extensive power-to-gas use to be more than outweighed as the need for electricity transmission network expansion is reduced, less flexibility in the form of battery storage and gas-fired generation capacity is needed and additional investments in a heat sector that remains partly gas-based become redundant. Klein et al. suggest total societal cost savings for Germany of EUR 19 billion until 2050, even though they leave aside the additional upsides of the savings in expansions of the electricity distribution network and the advanced utilization of biomethane potentials [6]. This conclusion is supported by nymoen with similar results [4].

A third category of studies formulates the central expectation that a major share of renewable gases will be imported from outside the EU. Despite the costs for these imports, Hecking et al. estimate for Germany societal cost savings of EUR 129 billion until 2050, arguing along the same lines as the above studies. In particular, they cite redundant investments into gas-fired generation capacity, redundant replacement of appliances and building insulation by end-users and reduced costs for electricty network expansion and imports; they do not even monetize adaptations by industrial end users and a potential dismantling of infrastructure, which could further support the overall result [23].

3.1.2. Arguments against potential gas sector contributions

<u>Gas-based energy end use is often less efficient than alternatives</u>: With regards to the residential sector, electric heat pumps are considered to be the potentially predominant technology for replacing gas-fired appliances. We must acknowledge that such heat pumps are already substantially more efficient than gas-fired boilers or conventional electric heating systems and that they develop rapidly [9, 13]. In contrast to gas-fired boilers, however,

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heat pumps deliver low-temperature heat which requires specific heat delivery systems (mostly floor heating) and proper building insulation [6]. Also, heat pumps are highly efficient on average, but their specific efficiency directly correlates with the outside temperature, i.e. heat pumps consume most electricity in periods of high peak load. This needs to be accommodated in the electricity network.[k]

A substantial increase of the share of heat pumps e.g. in residential heat delivery will increase the efficiency of end use heat generation but will create issues and costs further up the supply chain [6, 26]. This is especially true where buildings which are currently heated with natural gas need to be adapted for heat pumps [4, 9].

The efficiency argument is valid beyond the residential sector. A typical example is industrial high-temperature heat, which is largely gas-based for efficiency reasons [26].

<u>Methane leaks into the atmosphere</u>: The International Energy Agency reports that methane to the amount of 1.7% of global natural gas consumption currently leaks into the atmosphere [45]. Given the fact that methane is as greenhouse gas several times more harmful than carbon dioxide, this drives global warming beyond proportion. While methane leakage reportedly occurs along the entire gas supply chain, most of it can be attributed to production and processing as well as the long-distance transport of natural gas. Replacing natural gas delivered to Europe from distant sources by renewable gas produced within the EU or nearby could keep this issue in check [45].

<u>Biomethane production may raise sustainability issues</u>: Biogas and biomethane production have been criticized for displacing food and feed production, for negative effects on land use and for harming biodiversity or soil quality [13].

To counter these effects, the European Union has introduced and is about to update [48] mandatory sustainability criteria for biofuels [42]. In addition, national measures could already be in place to ensure that the primary source of feedstock is waste materials [29].

To avoid any ambiguity related to the sustainability of biomethane, even if produced in compliance with the applicable standards, some of the studies we analyzed take an alternative approach and focus on waste material exclusively [13]. This is closely related to the circular economy objective addressed earlier in this paper.

3.2. Enabling factors for gas sector contributions to a future EU energy system

After discussing arguments in favor and against the gas sector as part of a climate-neutral EU energy system in the previous chapter, in this chapter we focus on research question 2: the enabling factors for such a contribution. The results we present here were developed in a focus group process that was conducted to input to the Austrian climate and energy strategy and that also covered the potential role of the gas sector in this overall future concept.

Our results are based on the justified assumption of Papp et al. that the Austrian gas sector can gradually replace by 2050 at least 23 TWh of natural gas through renewable gas [24]. This allows to cover the entire gas demand of the buildings sector.

To realize this capability, several changes to the current energy system framework are required. These are enabling factors that are integral to a potential gas sector contribution to a climate-neutral energy system. We outline them in the following.

Commercial incentives for investments in GHGE abatement measures: All participants in the discussions agreed that GHGE abatement costs related to the use of renewable energy sources in general and the use of renewable gases in particular are not sufficiently reflected in energy market prices at the moment. Public support schemes with substantial sums will be required to actually move development towards climate neutrality [49]. This is also important for renewable gas production technologies, which are currently not cost competitive when compared to conventional or alternative technological approaches. However, they are considered important from a broader energy system design point of view and they do show substantial learning rates.

Participants discussed market-based tendering of renewable gas generation capacity as an appropriate solution. The purpose of such a mechanism should be to establish favorable and predictable investment conditions that facilitate increasing renewable gas volumes based on the potentials identified, so that they can gradually replace natural gas in the building sector (in spite of the market conditions already outlined). The level of support granted by this mechanism should also differentiate between the different technologies that can be used to produce renewable gases, since each of them has different potentials and different technology readiness levels.

Fair financing of such incentives: In principle, the mechanism should be financed through a dedicated component of the gas network tariffs that is levied on consumption and payable by gas end users. Participants considered this to be important to avoid undue cross-subsidies; also, a similar levy already applies for electricity.

There was controversy about which groups of gas customers should have to pay such a levy. While the general concept aimed to position renewable gas in the buildings sector, this differentiation can hardly be made from a technical/organizational network perspective. This led to different views about whether the levy should only apply to residential end users of gas and SMEs or whether gas consumers with larger consumptions, such as the industry, should also have to pay it. It was argued that, while electricity cannot be substituted by end users, gas directly competes with alternative energy carriers. Cost allocation can have a substantial impact on the competitiveness of businesses and on energy affordability throughout society.

Level playing field for all renewable energy carriers: All participants agreed that the public image of renewable gas and awareness in relation to its positive impact need to be improved to realize the identified potentials, and that it should be considered in housing subsidy schemes and building regulation. While recognizing that these frameworks are anchored at regional level in Austria and that issues of national coordination exist even today, all agreed that renewable gases should be integrated. For instance, gas-fired heating systems should not automatically be considered to be fossil fuel based and thus be banned from new buildings or renovation of existing ones (as is the case for oil) [46]. Instead, depending on the actual level of renewable gas injected into the system as a result of the tendering mechanism, gas-fired heating should be considered to be renewable. In line with the principle of technology neutrality, heating installations based on renewable gas should receive the same housing subsidies as other renewable heating systems. The discussion revealed different options for implementing such a model: Either the institution responsible for the tendering mechanism and for monitoring actual renewable gas injection and the institutions that grant housing subsidies could coordinate their actions directly; or renewable gas certificates could be used by gas suppliers to prove to end users that their gas is indeed renewable and they could serve as basis for housing subsidies. The second option would require a system of certificates of origin that guarantees the renewable nature of gas, similar to what is already in place for renewable electricity.

Legal clarifications: More in general, supporting renewable gases requires a universal legal definition of renewable gases; the relevant legislation at European and national level does not provide a sufficient definition at the moment. For legal and regulatory purposes, it must also be clarified whether and in which way existing tariff and taxation components apply to new renewable gas production technologies.

Innovation incentives: Participants agreed that public support for renewable gases should also extend to research and development, which is necessary to facilitate innovations in all relevant areas.

3.3. Overview of main results and general discussion

In order to achieve the GHGE reduction goals laid down in the Paris Agreement, the EU energy sector will have to undergo a substantial transformation and become virtually climate-neutral by 2050. Fossil fuels need to be faded out gradually, energy efficiency measures have to be identified and renewable generation capacity based on wind, solar, biomass, etc. must be expanded substantially.

Our review of relevant studies mostly reveals arguments in favor of a contribution by the gas sector in such a context. It can facilitate the transition to a climate-neutral European energy system and be a long-term element in it. More precisely, the role of the gas sector need not be limited to balancing renewable electricity generation and demand through power-to-gas and the existing gas infrastructure. Given the available technologies and identified potentials to produce large volumes of renewable gas from renewable electricity as well as an optimized use of biomass in a circular economy setup, renewable gas could support climate-neutral energy end use through the utilization of existing infrastructure in the public domain (networks, storages) and through end-use appliances (combustion and heating systems, etc.).

While renewable electricity can be expected to become substantially more important, renewable gas could ensure efficient long-term utilization of the existing gas infrastructure and reduce the magnitude of electricity network and storage expansion required, which would positively impact overall investment needs. Moreover, a well-defined role of renewable gases could help to reduce the public acceptance issue that is usually experienced with electricity infrastructure projects. Being able to utilize the existing gas infrastructure for this purpose could thus also contribute to speeding up the transition process towards a climate-neutral energy system.

Arguments against an involvement of the gas sector in a climate-neutral energy system include the relatively low efficiency of gas-based low temperature heat generation and other end uses, methane leakage and sustainability issues related to biomethane. These need to be considered with the necessary prudence when designing energy policy. However, when taking a holistic view of total energy system costs based on overall system architecture, options with a role for gas infrastructure and renewable gases show substantial societal cost savings in comparison to mostly electricity-focused models. With regards to the societal cost savings, further research could validate this review conclusion in a quantitative way while maintaining the holistic approach of our qualitative analysis.

While most of the reviewed studies were prepared or commissioned by organizations close to the gas sector, similar views have been expressed by the European Commission and the Council of European Energy Regulators; these can be expected to take a neutral stance with the aim of optimizing the energy supply chain as a whole, across the different energy sources and carriers. Nonetheless, further research could pay particular attention to additional views of further energy sector stakeholders.

Beyond the potential contributions of the gas sector, we also examined enabling factors that are needed to unlock such gas sector contributions. We took an empirical approach and focused on the Austrian case. While the combination of enabling factors identified in this paper might not be the optimal solution for other member states, and while different national characteristics and potentials could lead to different approaches, some central observations are considered to have general validity. Firstly, the expected societal benefits of a long-term gas sector contribution to a climate-neutral energy system are not currently reflected by the market prices for energy and carbon. The investments that would be required and that have long-term societal value thus become uneconomical for individual investors; public intervention will be required to initiate the transition process to a climate-neutral energy system. Secondly, several adaptations to the regulatory framework would be required to ensure a technology-neutral approach and give renewable gases the possibility to be properly positioned in such a system. This refers to both specific energy market regulation and the conditions relevant for energy end uses such as building regulation, etc.

Along these lines, the focus group discussions with Austrian gas sector experts revealed the need for a public support scheme with market-based tendering of renewable gas generation capacity, financed by a levy payable by gas end users. When allocating the costs of such a support scheme, the potential direct social impact in the residential sector and the influence of the competitive cost position in the industry sector must be considered. This holds true for the allocation of network costs in general and underlines the need for a sufficiently high utilization rate of the gas infrastructure across network levels as a prerequisite for a cost-effective supply of renewable gas to end users. Further research could assess this crucial aspect and the implications of such refinancing and cost allocation models in greater detail.

As a general requirement, there should be a universal definition of renewable gases in relevant regulations, and renewable gas should be eligible for housing subsidies on the same footing as renewable electricity; this would establish a level playing field for different technological approaches with a comparable climate impact.

4. Conclusions

Our results show that the gas sector could perform a variety of functions in a future EU energy system and its energy supply chain. For one, the limited potential of pumped-storage hydro and both the commercial and technical characteristics of battery electric storage call for utilizing the gas infrastructure at least for seasonal storage. Beyond that, using the existing gas infrastructure for delivering renewable energy in gaseous form to end users is expected to provide various positive effects, such as (i) reducing the substantial electricity network expansion needs, (ii) providing a renewable alternative for final energy needs that cannot be met with electricity for technical reasons, and (iii) limiting adaptation requirements for end-use appliances.

Renewable gas will either be generated from volatile sources such as wind and solar power in power-to-gas processes or be the result of an extensive cascading use of biogenic resources in line with circular economy principles. These technological solutions for producing renewable gas as a climate-friendly alternative to natural gas are in place and investment costs are expected to decrease substantially as economies of scale develop. While renewable gas can be produced in the EU, a significant share is expected to be imported from regions with competitive cost advantages outside of the Union. The import and transit infrastructure currently used for natural gas can continue to be utilized for this purpose in a sustainable manner.

Ultimately, the results show that a well-defined contribution of the gas infrastructure and renewable gases to the establishment of a climate-neutral EU energy system can (i) speed up the transition, (ii) increase the public acceptance required for the long-term sustainability of a policy framework in line with climate targets, and (iii) provide societal cost savings when considering energy system costs in a holistic way.

Nonetheless, substituting natural gas by renewable gas and using the gas infrastructure for storage and transport of renewable electricity will require public intervention. More precisely, these technologies need to be properly reflected in policy, favorable and reliable conditions for investments in the further development and market roll-out of these technologies need to be put in place, and a level playing field based on the principle of technology neutrality needs to be ensured. Our empirical analysis of the Austrian case identified one possible approach: A market-based tendering mechanism for renewable gas generation capacity with differentiated cost allocation among gas end users and utilization of this renewable gas in the residential sector on the same basis as renewable electricity.

If such conditions are established, renewable gas and the gas infrastructure could indeed be expected to be an integral part of the climate-neutral EU energy system of the future.

List of abbreviations

CCS	carbon capture and storage
CCU	carbon capture and utilization
CO2	carbon dioxide
EU	European Union
EUR	euro
GHGE	greenhouse gas emissions
IEA	International Energy Agency
km	kilometers
RES	renewable energy sources
SMEs	small and medium-sized enterprises
TWh	terawatt hours

Declarations

Availability of data and materials

All data which support our conclusions are presented in this paper. The original transcripts of focus group sessions are not published to protect the privacy of the discussion participants.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Both authors designed the objectives and methods of this paper and contributed to the conclusions. CL carried out the review and analyzed the empirical data, while HS designed and conducted the underlying empirical study. Both authors read and approved the final manuscript.

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Endnotes

[a] While the basic carbon capture and storage (CCS) technology has been thoroughly addressed by academic and industry-driven research, and while small-scale installations already exist, in many countries it can be considered to be a politically sensitive issue. Moreover, the increasing competitiveness of RES in combination with improving economic efficiency of power-to-gas put CCS under particular pressure [7].

[b] As a consequence, investment costs for solar and wind generation capacity dropped substantially. According to the IEA, the average investment costs for onshore wind dropped by 35% in the period 2008-2015, the costs for

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solar by 80% [15]. This development is expected to continue, with renewables being the predominant energy source.

[c] This is based on a systematic search of relevant journal publications in the databases Web of Science, Science Direct and Springer Link.

[d] The EU Energy Roadmap articulates the expectation of a share of electricity in final energy consumption that increases from 22% today to 35-40% in 2050 [1].

[e] Beyond the seasonal storage function, gas storage could also function as flexibility service and support short-term electricity network balancing [4, 5]

[f] There is a similar concept known as “power-to-liquids”: Hydrogen produced in the same way as for power-to-gas is subjected to a subordinated process (primarily, the “Fischer Tropsch” process) to be transformed into renewable synthetic liquid biofuels such as kerosene, diesel and gasoline. These could be used together with existing engine technologies to reduce GHGE in e.g. the transport sector [6].

[g] According to the Natural Gas Vehicles Association, the market penetration of natural gas fueled passenger cars in the EU is highest in Sweden at 0.4%. For trucks, the leading EU countries show a market penetration between 2.5 and 4% [8].

[h] For the case of Germany alone, theoretical dismantling costs for the gas transport infrastructure amounting to EUR 20 billion have been reported [9].

[i] While 75% of the existing building stock is energy inefficient, only 0.4-1.2% of buildings across EU member states are renovated each year [11].

[j] One of the studies we analyzed models the German electricity and gas networks in detail. It estimates that the involvement of renewable gases can avoid 500,000 km of electricity distribution network expansion in Germany alone. Currently, there are 1,500,000 km of electricity distribution networks, and their capacity will need to be expanded [9].

[k] There may also be hybrid solutions with heat pumps that are gas-fired instead of using electricity as input fuel or heat pumps which are predominately electricity-driven but include an additional gas boiler to cover peak heat demands. This may reduce the implications for network capacity and for the required insulation of houses. However, The efficiency of this heat generation process is lower than for the electricity-only version [13].