HOW AND TO WHICH EXTENT 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 in which renewable energy sources ultimately replace fossil fuels such as natural gas. In this context, the question how and to which extent the gas sector can contribute to an increasingly climate-neutral future EU energy system is heavily debated among scholars, energy industry experts and policy makers.

Methods: We take a two-step approach: We begin with a review of studies from energy industry and academia to discuss potential gas sector contributions from a holistic energy system design point of view; this is followed by a comprehensive discussion of technical potentials, micro-economic conditions and societal implications of renewable gas. We then enrich our findings with the results of an empirical focus group process.

Results: The gas sector can not only contribute to balancing volatile renewable energy production but also enable the supply of renewable energy to end-users in gaseous form; based on existing infrastructure. This could reduce costs for society, increase public acceptance and ultimately speed up the energy system transformation. There is the theoretical technical potential to substitute major parts of natural gas with renewable gas of biogenic and synthetic nature. This, however, crucially requires a supportive policy framework like the one established for renewable electricity.

Conclusion: Given the societal benefits and the competitiveness of renewable gas as compared to renewable alternatives, energy policy makers should incorporate renewable gas and the existing gas infrastructure in the future energy system framework. The objective should be an optimized interplay of various energy vectors and their infrastructure along the entire energy supply chain. This requires a level playing field for different renewable technologies across different policy areas and a form of public support that strikes the balance between facilitating the gradual substitution of natural gas by renewable gas while maintaining public acceptance for this transformation despite higher costs for end-users.

Keywords: energy system, energy policy, climate neutrality, renewable gas, biomethane, power-to-gas, technical potential, support level

JEL classification: O13, Q42, Q48

1. Background

Europe's gas sector currently covers between 20 and 25% of the overall European final energy demand [2]; its powerful high-pressure network has a length of 240,000 km [4]. 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. However, the gas sector with its extensive network and storage infrastructure might have a sustainable future beyond fossil fuels, beyond natural gas.

Indeed, this notion is already addressed in literature from different perspectives. There are papers such as Wall et al. or Götz et al., dealing with renewable gas production pathways [8, 9]. The technical potential of these production pathways is also addressed by Baldino et al., Scarlat et al. and others [12, 13]. On the commercial side, papers such as Paturska et al., Thrän et al. and Papp et al. deal with the micro-economic conditions for renewable gas production in different settings [10, 16, 17]. While the scholarly discussion of renewables support policies is currently focused on electricity, the papers by e.g. Budzianowski et al. and Repele et al. provide some findings specifically for renewable gas, at least from a theoretical perspective [20, 21]. Beyond that, there are various studies prepared or commissioned by academic institutions but also industry organizations close to the gas sector that outline the potential and economic benefits of renewable gas for different geographic scopes, for different energy end-use segments and based on different assumptions with the presumed aim to raise awareness for these aspects among energy policy makers [14, 15, 18, 19, 25].

What is missing, however, is an integrative approach that brings together these various research streams to critically discuss how and to which extent the gas sector can contribute to an increasingly climate-neutral future EU energy system. Applying, for the first time, such a holistic approach to the matter enables us to contribute to closing three major research gaps: (i) the specific functions and potential contributions of gas in a future EU energy system's supply chain, (ii) the required level of public support and resulting major societal implications of such gas sector contributions, and (iii) the implications that a future EU energy system including renewable gas has for policy making.

Specifically, this paper is the first theoretically guided compendium of potential contributions of the gas sector to the establishment of a climate-neutral EU energy system. These contributions have been identified based on a review of studies and analyses done by energy industry organizations and academia. To derive from such review implications of practical relevance for researchers and policy makers, it is complemented by a comprehensive critical discussion of the theoretical volume potential of renewable gases, an assessment of micro-economic conditions for the production of renewable gas as well as its societal implications vis-a-vis alternative renewable energy production pathways. These consolidated findings 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, which could be equally expected also in other EU member states, delivered conclusions about enabling factors in energy policy, energy regulation and beyond which are required for the gas sector to be able to deliver on its potential.

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

Already in 2011 the European Commission formulated the objective to reduce by 2050 their greenhouse gas emissions (GHGE) by at least 80% compared to the 1990 benchmark [27]. Simply spoken, this requires cutting GHGE by half in each decade to come [29]. However, since the European Union has committed itself to meeting the objectives of the Paris Agreement adopted in 2015 [30], the need for even stronger efforts has evolved. Consequently, the European Commission prepared in 2018 a new long-term vision towards achieving a climate-neutral economy with net-zero GHGE by 2050 [32]. In this context, it is explicitly articulated that the energy end-

use sector, which currently accounts for around 75% of total GHGE, will have to move towards climate neutrality. 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, or (iii) sequestering carbon dioxide for permanent storage in geological underground formations [32].

1.2. Overall objectives for 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 [5]. 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 [34]. 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 and maintain 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 several 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 [5, 36, 37]; this translates into the policy objective of reducing final energy demand by 20% by 2020 [38], and more than 30% by 2030 [40]. Secondly, fossil fuels as a 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 emissions from the use of fossil fuels [32]. This includes natural gas. Instead, 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, and there is a binding EU policy objective for the share of renewable energy to reach at least 32% by 2030 [41].

1.3. Specific role of gas in a future EU energy system to be defined

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 delphi survey about the future EU energy system with 450 experts formulated in 2016 the hypothesis of an "all-electric society" with electricity as single energy vector to emerge in the long run [42]. This, however, was recently scaled back by a study by the association of the European electricity industry which, in its most progressive scenario, expects electrification to not exceed 60% of total energy consumption. Also 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 [43]. This was confirmed by the European Commission's long-term vision for a climate-neutral economy, which was published in 2018 and which portrays an energy system integrating the various energy vectors, such as electricity and gas [32]. 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 should make best use of the potentials of the gas sector [34]. These include a finely meshed network that connects 118 million end-users[a] within the Union [44], comprehensive storage infrastructure, and the potential to substitute natural with renewable gas [34]. But again, specific measures for how to realize this objective are not yet sufficiently agreed or even defined in detail.

2. Methods

In this paper, we apply a qualitative strategy. To identify and discuss the possible contributions of the gas sector in a structured way, 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 twelve studies (see Table 1).

Table 1 Sample of studies reviewed [6, 14–16, 18, 19, 22–26, 28].

[Note: table placed at the end of the manuscript]

Half of the studies in the sample focus on Germany, where the extensive "Energiewende" debate has created substantial attention for energy system design issues. The other half of the sample is made up of studies dealing with the Dutch, French, British and Austrian or overall EU situation, and which arrive at similar conclusions.

Publications in academic journals that would be relevant for the present review have been few and far between; 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, industry organizations, etc. In addition, we used relevant findings from academic articles that cover specific aspects to enrich our review (see Table 2) and deliver on the discussion of technical potentials and micro-economic cost aspects of renewable gas.

Table 2 Articles dealing with specific aspects used to enrich the review results.

Aspect	References
Statistics and databases	[4, 45–48]
Renewable gas production technology	[8, 9, 49–54]
Technical potentials	[10, 13, 55]
Economic considerations	[17, 56, 57]
Legal/regulatory background	[32, 34, 40, 41, 58–62]
Methane leakage	[63–65]
Energy storage technologies and potentials	[66–68]
Hydrogen as an energy vector	[69–72]
Implications and developments on end-user side	[73–77]
Electricity grid issues	[78, 79]
Policy considerations	[80–83]

Based on the review and its discussion, we addressed 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. The Energy Institute set up a series of discussions with experts from the Austrian gas sector and social partners[b] involved in energy policy making. The objective was the development of a joint position as input to the process of updating the national climate and energy strategy by the Austrian government [61]. We can safely assume that comparable processes are also taking place in other countries, since the revised Directive on the promotion of the use of energy from renewable sources (Directive 2018/2001) requires member states to adopt national renewable energy action plans by 2020 [41].

Table 3 Details of focus group sessions.

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 the economy and 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 and moderated by the Energy Institute at Johannes Kepler University Linz. For the present paper, we performed a thematic analysis of the records of these discussions and of documents based on discussion results.

3. Results

We start out with our results on the potential contributions of the gas sector to a future EU energy system and its functions therein. In a next step, this is complemented by empirically derived enabling factors for such contributions.

3.1. Potential contributions of the gas sector to a future EU energy system based on the reviewed literature

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,[c] limited electricity system flexibility becomes an issue [14]. At the moment, it is generation capacity using fossil fuels that provides substantial system flexibility, but this will have to change in the long run due to the emissions it causes [32].

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 approximately the average EU electricity demand over five days [46]. Even the absolute maximum theoretical potential of pumped storage capacity is no more than 123 TWh [66].

Battery solutions for storing electricity are another option, but even though their efficiency increases and their cost declines rapidly, one of the studies we considered finds that they will not reach competitive investment cost levels by 2050 [14]. And even if they do, their self-discharge characteristics limit their potential for seasonal storage [14, 25]. However, considering that 2050 is still a long way away and that there are intensive research efforts, this assessment might change.

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 with an operational capacity of 1131 TWh [47] throughout Europe 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 [6, 67, 68, 70]. Also the gas network itself has large volumes of linepack at its disposal and can manage substantial pressure differences [6]. As we see, the gas network is easier to balance than the electricity networks and it the risk of end-user supply disruptions is lower [58].

Gas networks can reduce the need for electricity network expansion: Recent electricity network expansion plans have faced difficulties [78] and involve large investments [14, 18, 79]. Further adapting the network to RES and an

increased electricity demand will require further expansions at substantially larger scales [6, 14, 22]. 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 strains on the electricity network could be relieved by transporting renewable energy to end-use destinations through the gas network [14, 19, 22, 70]. 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 [14, 18, 25].

Replacing natural gas by renewable gas enables climate-neutral energy end use: The reviewed studies underline that the technological solutions for replacing natural gas with renewable gases are already in place. These gases would only create as much GHGE as were captured during their production and thus allow all gas consumed in the EU to be climate-neutral by 2050 [14, 17, 25].

Basically, renewable gases are produced either by turning biomass into biomethane or as synthetic fuels. 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 [8, 9, 49, 52]. 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 and sustainability principles [17,33,60], 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. This means that maximum value is to be extracted during usage, and residues are used for energy generation in a last step, but again at a maximum level [8, 55]. The European Commission has translated this vision into a zero waste program for Europe [59]. However, frequently used estimations of biomethane potentials tend to be based on a mindset which is not sufficiently coherent with these principles and are assumed to have a substantial upwards potential (see section 4.1. for a discussion of the technical potential). Considering the current overall EU import dependence beyond 50% and political objective to reduce this, decentralized, local biomethane production could support the achievement of this objective [14, 15]. This would also create new jobs and strengthen the rural economy [8, 14].

As already mentioned, renewable gases can be of biogenic origin but can also be produced synthetically, most prominently through power-to-gas. This latter technology uses e.g. water electrolysis to convert RES electricity first into renewable hydrogen and then, possibly, into renewable methane. It not only enables using excess RES generation instead of curtailing it [6, 22] but also unlocks roles for the gas infrastructure beyond pure storage. Hydrogen and renewable methane could become gaseous "energy vectors" to meet any final energy need based on renewable sources such as wind and solar [14, 22, 25, 69]. This particular avenue is envisaged by the initiative to turn the large-scale chemical cluster in the northern Netherlands into a hydrogen economy [26].

Hydrogen may also be produced based on fossil fuels and different technologies, such as it is currently done in the chemical industry [72]. In the context of a climate-neutral energy system, the resulting carbon dioxide then needs to be either permanently utilized or stored so that it does not enter the atmosphere [32]. This is planned for the H21 project in Leeds, where carbon dioxide will be compressed and sequestrated deep in the North Sea [28]. Another technological perspective for the future production of hydrogen is the pyrolysis process [53], which is investigated as potential future strategy by the major Russian gas supplier Gazprom [54].

While natural gas networks might be turned into pure hydrogen systems [28], the potential to blend hydrogen into the existing natural gas system is limited to single-digit percentage shares [14, 22, 69]. Higher percentages would require some adaptation of network infrastructure and end-use appliances [14, 71]. 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 [14, 16, 19, 50, 51].

Beyond the intra-EU potential for the production of renewable gas, there is also the possibility to import renewable gases [14, 19, 56]. 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 [14]. Hecking et al. and Bothe et al. also refer to the comparative cost advantages of production regions outside the EU and expect major imports in the long run [18, 19].

Irrespective of the specific origin of renewable gas, it can be used to meet various final energy needs [70]. While the extent to which renewable gases offer advantages over alternatives differs between sectors, there are potentials in all end-use segments. In transport, gas plays a minor role for the time being, and public acceptance is low [81, 84]. However, over time, renewable gas could develop into a relevant substitute for traditional liquid fuels and could help reduce transport-related GHGE; the vision for it exists, as does the technology needed to make it happen [70]. This option is particularly relevant for heavy-duty road transport, where electric drives face technological limits [14, 81].

The buildings sector, on the contrary, is still mostly based on fossil fuels in general and natural gas in particular [6]. Consequently, this sector is considered to be highly important for determining the role of gas in the future [14, 16, 19, 22]. While renewable district heating and electric heat pumps are often discussed as prime means of reducing GHGE in this sector [14], the studies we reviewed argue that renewable gas can make a beneficial contribution to a future energy system in this sector also [14, 16, 18, 19]. Proponents argue that, beyond the economic considerations of building owners in the context of heating system adaptations, continued use of existing gas infrastructure in the public domain would create added value for society as a whole [14–16, 18, 19, 22, 24, 26, 28].

The industry faces yet another different set of challenges. There are technological limitations to the direct use of electricity in high-temperature processes [6, 14, 18]. Nonetheless, the European steel-making industry, currently a major gas consumer, is exploring ways to electrify energy-intensive processes, e.g. by using electric arc furnaces instead of traditional blast furnaces [74]. Such research and development could lead to the technical limitations of electrification being overcome over time [73]. We cannot know yet how this would affect the competitiveness of the European industry on the global market [75].

The position of gas as a fuel for electricity generation directly depends on the intended phase-out of coal-based generation. In such a context, gas-fired generation could be a logical source of system flexibility that would help balance a RES-dominated electricity system [6]. 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 [6, 24]. To maximize energy efficiency, resulting waste heat should also be used.

<u>Utilization of readily available gas infrastructure requires little investment</u>: Given the fact that the natural gas infrastructure is already in place, renewable gases could be transported without large-scale gas network expansion. But making the gas networks ready for renewable gases, particularly hydrogen, will require some adaptation. A study that investigates in detail the cost of such adaptions in the German gas network concludes that it will be at a level of 25% of the replacement investment costs that are required to maintain the capacity of the network in any case [57]. Beyond that, Further necessary investments would be limited to connecting a significant number of biomethane production plants and power-to-gas facilities [14], which we do not expect to be significant [15].

Another feature of the European gas network and its major transit pipelines is the high level of interconnectivity between member states [26]. This could facilitate widespread use of renewable gas within the Union and provide efficient access to different potential production sources of renewable gas across the EU [19].

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 [14]. Looking at renovation rates, which are currently particularly low,[d] 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 [14]. If end-users continue using gas-fired appliances based on renewable gas, this could significantly speed up the transition [18]. This also holds true for industrial processes where alternatives to gas in some cases rarely exist or would require lengthy research and transformation processes [6, 14, 18, 25].

A gas sector contribution to a future energy system can mitigate public acceptance issues: Local resistance to large-scale renewable generation capacity construction can be substantial [76]. Also, the overhead lines common in electricity transmission are often perceived negatively by the affected local communities [14, 77]. And the public debate will not be long in picking up that an electricity-dominated energy market design will create the need for substantial expansions of the electricity distribution network also [6, 19, 22]. This contrasts with the gas infrastructure, which is already in place [14, 22]. Also, gas networks are mostly underground, so public acceptance is less of an issue [19].

Acceptance is important not just for infrastructure projects but also for activities on the end-user side, such as replacing heating systems and/or insulating buildings. The significance of these activities and the related costs go beyond societal considerations; indeed, they can be expected to be decisive for the long-term sustainability of policy objectives and measures directed at operationalizing climate targets [19, 76].

A gas sector contribution to a future energy system can foster security of supply: Renewable gases can be particularly valuable when it comes to maintaining a high level of security of supply [19, 22]: An energy system with multiple energy vectors is less concentrated and therefore more flexible in stress situations [18, 22, 82].

A gas sector contribution to a future energy system can ensure cost effectiveness from a societal perspective: 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 [14, 19, 22, 24]. All arguments in favor and against the potential role of gas need to be factored in when modeling societal cost implications. This should then be the basis for policy making [14, 19, 22, 24].

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 overall cost benefits.

One group of studies researches the impact of renewable gases based on the assumptions that power-to-gas uses domestic RES excess generation only and that considerable 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 € 138 billion per year by 2050; these are mainly generated as investments towards adapting residential heating concepts and massively expanding RES generation capacity and electricity networks become redundant [14]. These estimates are corroborated by Eurelectric, who expect that average annual investments at a level of €

90 to € 110 billion will be necessary to expand renewable generation and transmission capacity in an electricity-focused system [6].

Bothe et al. and Ecke et al. follow a similar reasoning, estimating societal cost savings in Germany by 2050 at € 12 billion [19] and € 4 billion per year [24], respectively. 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 [23].

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 € 19 billion until 2050, even though they leave aside the additional upsides of the savings in expansion of the electricity distribution network and the advanced utilization of biomethane potentials [25]. This conclusion is supported by nymoen with similar results [22].

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 societal cost savings for Germany to amount to € 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 electricity 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 [18].

3.1.2.   Arguments against potential gas sector contributions

Gas-based energy end use is often less efficient than alternatives: With regards to the residential sector, electric heat pumps are considered to be the potentially predominant technology for replacing gas-fired appliances [14, 22]. The reviewed studies acknowledge that such heat pumps are already substantially more efficient than gas-fired boilers or conventional electric heating systems and that they develop rapidly [6, 14, 19]. In contrast to gas-fired boilers, however, heat pumps deliver low-temperature heat which requires specific heat delivery systems (mostly floor heating) and proper building insulation [25]. 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. Consequently, a substantial increase of the share of heat pumps e.g. in residential heat delivery will improve the efficiency of end-use heat generation but will create issues and costs further up the supply chain [24, 25]. This is especially true where buildings that are currently heated with natural gas need to be adapted for heat pumps [19, 22].

The efficiency argument is valid beyond the residential sector also. A typical example is industrial high-temperature heat, which is largely gas-based also for efficiency reasons [6, 24].

Methane leaks into the atmosphere: 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 as greenhouse gas is several times more harmful than carbon dioxide, this drives global warming beyond proportion [13, 63]. While methane leakage 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 [63]. Replacing natural gas delivered to Europe

from distant sources by renewable gas produced within the EU or nearby could improve the situation [45]. A recent study with a focus on methods to determine methane emissions in EU gas distribution systems finds that less than 10% of total methane emissions by EU member states are actually the result of methane leaks; while the largest culprits are the agriculture and waste sectors [65]. Nonetheless, against the background of a climate-neutral energy system this issue should be considered with caution. Since from a technical perspective, it is almost impossible to fully eliminate all fugitive methane emissions of the methane supply chain , the gas sector should set up coherent measurement standards and methods to ensure transparency [65], and continue to minimize such emissions to the extent possible [63, 64].

Biomethane production may raise sustainability issues: 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 [14]. This is a crucially important argument, since the prioritized use of RES must not sacrifice the high-level principle of strengthening our economy's sustainability.

To counter these effects, the European Union has just tightened mandatory sustainability criteria for biofuels [41]. In addition, national measures can be passed to ensure that the primary source of feedstock is in line with sustainability principles [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 do not consider energy crops as feedstock at all [15, 16]. 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 having discussed arguments in favor and against the gas sector as part of a climate-neutral EU energy system in the previous chapter, we focus on the specific enabling factors for such a contribution in this subchapter. The results we present here were developed in a focus group process that was conducted to input to the Austrian climate and energy strategy by outlining the potential role of the gas sector in this overall future concept. The focus group comprised experts from the Austrian gas sector and social partners involved in energy policy making (see section 2. for details). The considerations and arguments presented are based on the assumption by Papp et al. that the Austrian gas sector could gradually replace at least 23 TWh of natural gas by renewable gas by 2050 [16]. This represents around 25% of the current total natural gas demand [48] and allows for covering the entire gas demand of the residential sector by that time. The focus groups concentrated on the changes to the current energy system framework that are required to realize this capability. We therefore consider them as enabling factors for such a gas sector contribution to a climate-neutral energy system. We outline them in the following.

Commercial support scheme for renewable gas production: All participants in the discussions agreed that GHGE abatement costs related to the use of RES in general and the use of renewable gases in particular are not sufficiently reflected in current energy market prices. There was general agreement that public support schemes of substantial extent will be required to actually move development towards climate neutrality. This is also crucial for renewable gas production technologies.

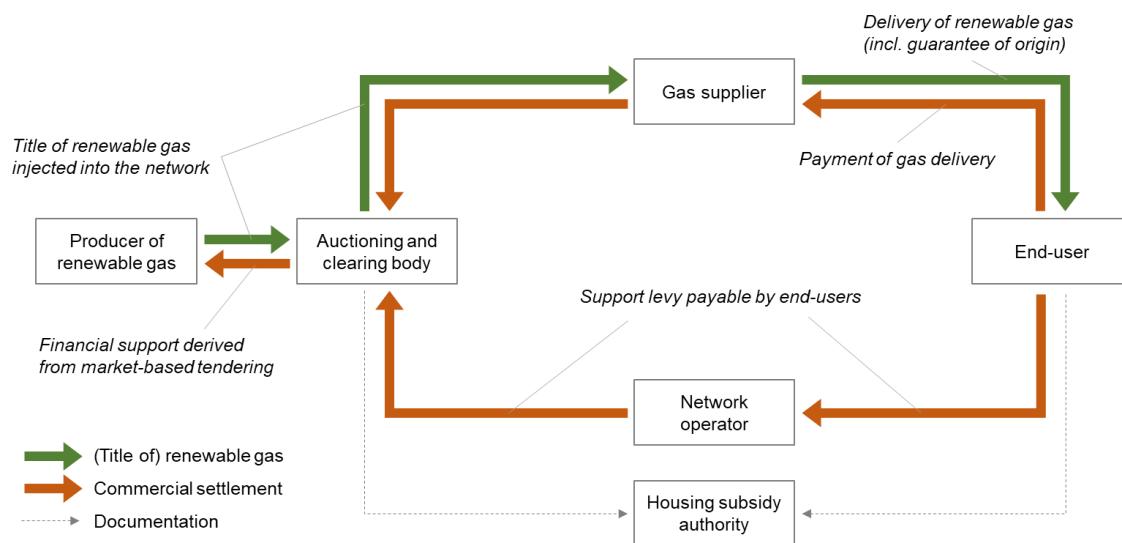
Such support schemes should especially involve feed-in tariffs or feed-in premiums over a period of at least ten years. Lately, there has been a move towards market-based determination of support levels [41, 62, 83]. To account for this development, auctions should be established for this purpose. They should be run by a responsible authority ("auctioning/clearing authority") and be based on the intended penetration path of renewable gas. This is expected to create favorable and predictable investment conditions and facilitate renewable gas production. In addition, the support scheme should differentiate between renewable gas production technologies to reflect their different potentials and different technology readiness levels.

Fair financing of support instruments: In principle, the support scheme 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 non-tax levy already applies for electricity.

There was controversy about which groups of gas customers should have to pay such a support levy. While the general concept aimed to position renewable gas in the buildings sector, this differentiation can hardly be made from a technical/organizational point of view. This led to different views about whether the support levy should only apply to residential end-users of gas and small and medium-sized enterprises (SMEs), both connected to the low-pressure level, or whether gas consumers with larger consumptions (connected to higher-pressure levels), such as the industry, should also have to pay. This was considered a crucial issue. In contrast to electricity, which can hardly be substituted by end-users, gas competes with other (fossil) energy carriers. Therefore, allocating the cost incurred by the support scheme for renewable gas producers needs to strike the right balance between broad socialization and protection of particularly price-sensitive end-users. This is considered important for maintaining competitiveness of businesses and energy affordability throughout the population [75].

Level playing field for all renewable energy vectors on the end-user side: 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. In particular, renewable gas should be considered in housing subsidy schemes and building regulation. 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 [61]). Instead, depending on the actual level of renewable gas injected into the system as a result of the support scheme, gas-fired heating should be considered 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 operationalizing such a model. In principle, however, there needs to be an auctioning/clearing authority that organizes the auctions and acts as contract partner for renewable gas producers for the entire support period. Additionally, this entity should transfer ownership of the volume of renewable gas that producers inject into the network to gas suppliers. In doing so, priority should be given to suppliers of gas end-users who receive housing subsidies. Such end-users need to provide proof that they are using renewable gas so as to remain eligible for their housing subsidies; this proof could either be provided through direct cooperation between the auctioning/clearing authority and the public institution responsible for housing subsidies ("housing subsidy authority") or by the end-users using guarantees of origin provided by their suppliers. This could be easily achieved since a guarantees of origin scheme for electricity, gas, heating and cooling delivered to end-users must be established by mid-2021 in any case [41]. With regards to commercial settlement, suppliers would pay the auctioning/clearing authority the market price for the volume they receive. The support levy would be collected from gas end-users by network operators and transferred to the auctioning/clearing authority to compensate it for the support paid to renewable gas producers (beyond the market price). Figure 1 provides an illustration of this process.

Figure 1 Schematic illustration of the discussed support scheme based on empirical focus group results.

Legal clarifications: There was agreement that supporting renewable gases requires a universal legal definition of renewable gases; the relevant legislation at European and national level does not provide 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. By way of example, the Northern Netherlands Initiative aims to help establish hydrogen innovation centers to develop technologies and business concepts, as well as to educate the workforce and the public.

4. 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 phased out gradually, energy efficiency measures must take effect renewable generation capacity must be expanded substantially.

Our review of relevant studies mostly reveals arguments in favor of gas sector contributions, assuming that 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. Renewable gas produced from renewable electricity as well as an optimized use of biomass in a circular economy could support climate-neutral energy end use through the utilization of existing infrastructure in the public domain (networks, storages) and through existing end-use appliances (combustion and heating systems, etc.). This appears to be in line with the views of European policy makers and regulatory bodies [32, 34] as well as the industry association of the European electricity industry [6].

However, renewable gases play a minor role for the time being. With 19 TWh of injection into the gas grid by 540 plants in 15 European countries [85], biomethane represents less than 1% of total EU gas consumption [86]. For power-to-gas, the current focus of the 128 installations in 16 European countries is clearly on research and their contribution to European gas supply is, for the time being, negligible [87].

The reviewed studies argue that the technologies to produce renewable gas of both biogenic and synthetic nature are already in place. However, it can be assumed that broad market penetration requires not only sufficiently

developed technological solutions but also the actual technical potential in terms of resources, feedstock, etc. as well as a favorable policy framework and sufficiently attractive micro-economic conditions for investment into renewable gas production. To address this aspect, we discuss the technical potential for renewable gas production and its micro-economic conditions in greater detail below, including its societal implications. By doing so, we do not provide an overall optimization of the energy system or indicate the optimal share of renewable gas in technical or economic terms. Rather, we derive the above-mentioned characteristics of renewable gas from various sources and bring them into an integrated energy system perspective, including the volume and cost side and a comparison with renewable electricity. This aims to take the academic debate of renewable gases to the next level and to support energy policy makers.

4.1.   Technical potential for renewable gas production

Due to significantly different technological avenues for the production of biogenic and synthetic renewable gas, we differentiate our discussion of potentials accordingly. For biomethane, we must bear in mind that the vast majority (89%) of the biogas produced is not currently upgraded to biomethane and injected into the gas network, but rather used on-site for electricity and/or heat production [31]. This, however, is mainly the result of national support policies incentivizing especially use in the electricity sector [31].

In its assessment of the potential of biogas in the EU beyond 2020, the European Commission includes a scenario of priority gas grid access for biogas [31]. Literature provides various arguments in favor of gas grid injection, such as (i) that biogas can replace fossil fuels in applications where other renewable alternatives are scarce [31], (ii) that biomethane is very flexible because it can be easily stored in gas storage facilities and distributed via the gas grid [12], and (iii) that biomethane offers much better end-use efficiency[e] than on-site electricity generation based on raw biogas [10, 11].

We refer to existing literature to assess technical biomethane potential. It is important to note that we do not consider the absolute amount of biomass residues theoretically available for biomethane production but only those volumes explicitly classified as biomethane. Since biogenic origin does not in itself ensure that potentials are used sustainably in a broader context, and since there are concerns related to biogas/biomethane (for further details, see section 3.1.2. and the papers by Scarlat et al. and Boulamant [12, 88]), we leveraged the level of detail provided in the relevant literature to exclude at least potentials that are predominantly based on energy crops as a feedstock. Instead, we focus on sewage sludge and particularly residues form the agricultural, forestry, industry and municipal sectors.

Table 4 Technical biomethane potentials for 2030/2050 in relation to projected total EU gas demand (based on [12–14, 31, 33, 35, 39, 89]).

Source/ Scenario	Ref.	Bio-methane potential 2030 (TWh)	Gas demand 2030 based on EU28 Reference scenario (TWh)	Share of total demand possibly covered by biomethane in 2030	Bio-methane potential 2050 (TWh)	Gas demand 2050 based on EU28 Reference scenario (TWh)	Share of total demand possibly covered by biomethane in 2050	Remarks
Baldino et al.	[13]	170		6%	290		11%	Only sustainable feedstock considered
European Commission	[31]	360		13%	n.a		n.a.	Technological focus on digestion process, gasification out of scope
Mathiasson. (only digestion)	[33]	300		11%	n.a		n.a.	Technological focus on digestion process, gasification out of scope
Mathiasson (digestion and gasification)	[33]	500		18%	n.a		n.a.	Consideration of both digestion process and gasification technology
Scarlat et al.	[12]	300	2803	11%	510	2752	19%	Only residues and sewage sludge are considered; 2050 value represents full technical potential
Searle et al.	[35]	n.a.		n.a	360		13%	Only residues are considered
van Melle et al.	[14]	n.a.		n.a	980		36%	Incl. cover crops based on sequential cropping strategies
Kovacs et al. (without energy crops)	[39]	340		12%	1030		37%	Only residues are considered
Kovacs et al. (incl. limited energy crops)	[39]	500		18%	1510		55%	Additional scenario including most conservative energy crops potential

Table 4 provides an overview of the biomethane potentials estimated in literature for the years 2030 and 2050. We compare these potentials with the officially projected EU gas demand for these years [89]. According to this results biomethane could cover between 11 and 55% of the projected total EU gas demand by 2050. In this context, it is worthwhile considering the structural configuration of the gas network. The transmission network is operated at high pressure and enables large volume transit, cross-border interconnection and supply to distribution networks; only the largest end-users, such as gas-fired power plants and heavy industry, are directly connected to this network level [90]. The majority of gas end-users, such as households and SMEs, are connected to the distribution level. Biomethane will be predominantly injected into this distribution network [90].

Figure 2 Historical EU natural gas consumption per sector (based on [86]).

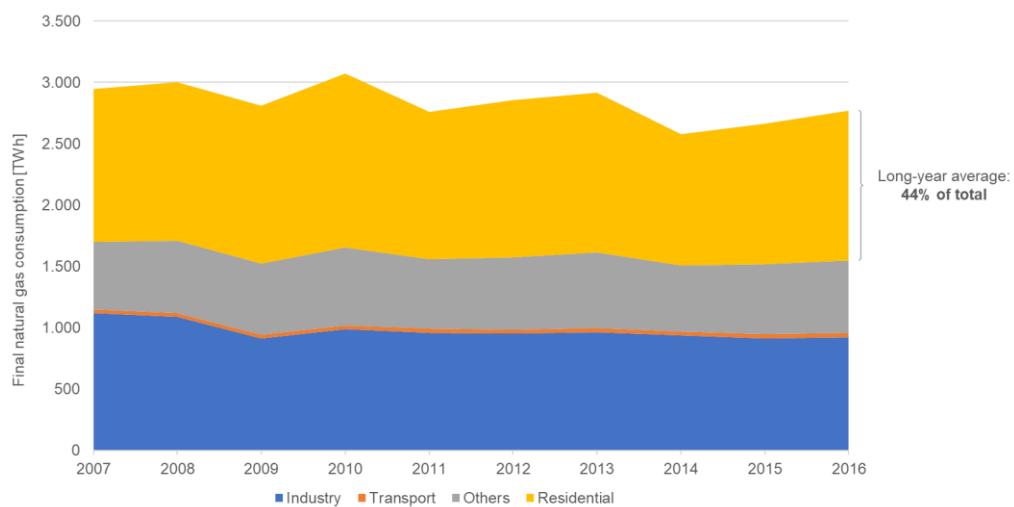
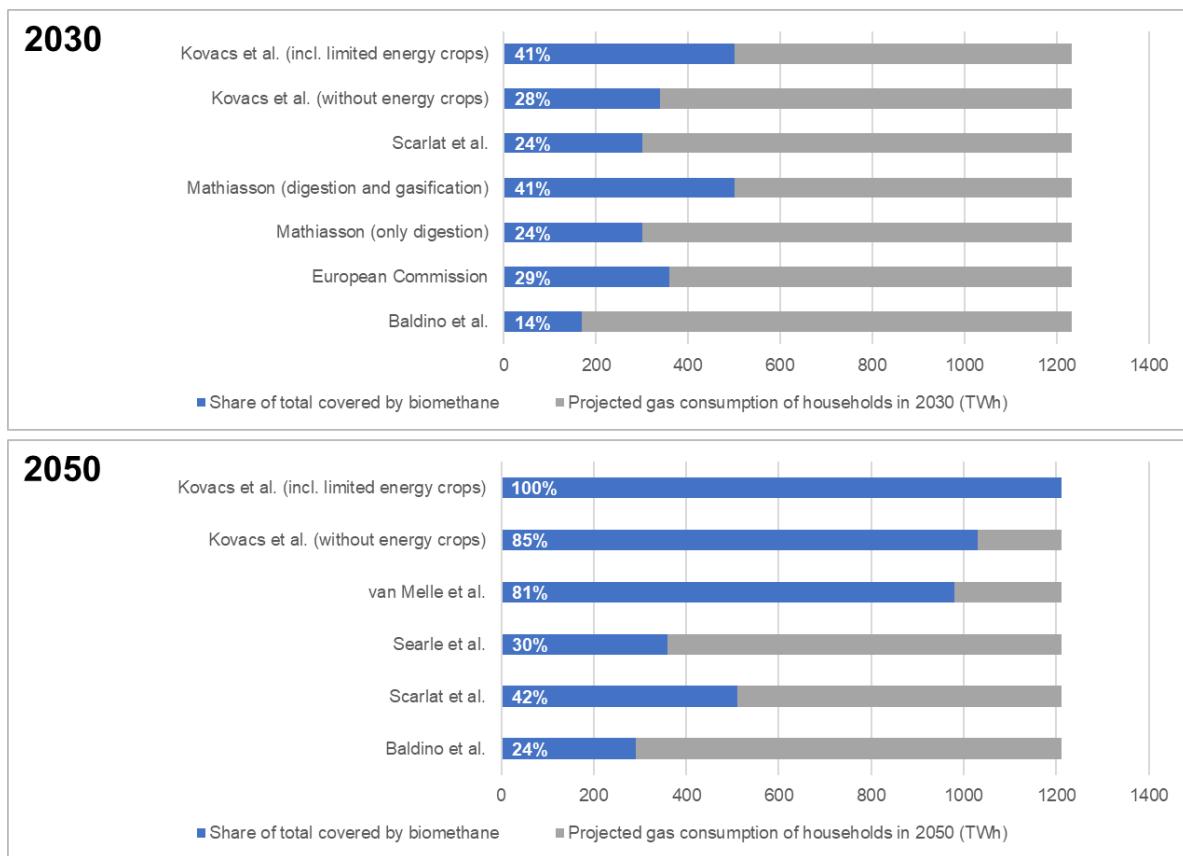



Figure 2 shows the long-term average share of household gas consumption in total gas consumption at 44%. If we assume that this share stays the same in 2030/2050 (at a time when, according to official projections for both years, total gas consumption will be down by only 10% approximately from 2016 levels [89]), this adds a new perspective which is illustrated with Figure 3. The technical biomethane potential in 2050 could cover between 24 and 100% of household gas consumption. Notwithstanding the need for seasonal balancing, this could go a long way towards uncoupling the distribution level from the transmission network, which serves as the main supply route today. While we expect potentially significant national differences, which could be addressed by further research at country level, this could indeed be a significant step towards achieving the policy objectives of climate-neutral energy supply and reduced import dependence [5, 32]. This conclusion coincides with the empirical results presented in section 3.2. which also envisage that natural gas supplied to Austrian households will ultimately be substituted by renewable gas; being predominantly biomethane [16].

Figure 3 Technical biomethane potentials in the EU for 2030/2050 in relation to projected households gas consumption (calculations based on data from Table 4 and [86, 89]).

With regards to synthetic renewable gas, the assessment of the technical potential follows a different logic. In contrast to the feedstock for biomethane production (i.e. biogenic residues/biomass), the predominant RES for power-to-gas applications (solar and wind energy) are nearly inexhaustible. Consequently, the only limits that apply on the pure technical potential for synthetic renewable gas are (i) land-use restrictions for e.g. wind and solar installations which limit the amount of renewable electricity that can be generated [22, 91, 92], (ii) the availability of electrolysers as part of a supply chain that is growing dynamically but even so, is only just developing [93], and (iii) limited carbon dioxide supply for producing synthetic methane [50, 92]. The effective technical potential, however, will rather result from the overall energy system design. The most relevant parameters in this context are expected to be the share of volatile renewable generation, the degree of electricity network expansion, excess generation curtailment principles, etc. [14, 19, 94]. In addition, structural parameters such as interconnection capacity between markets, the potential for carbon dioxide storage, etc. will weigh in [94–96]. Consequently, the effective technical potential is case-specific. Blanco et al., in their recent paper, use a scenario-based approach to model the potential of renewable methane in a largely climate-neutral EU energy system. This allowed them to vary key parameters across their 120 scenarios, accounting for different circumstances (such as those outlined above) [97]. With regards to the effective technical potential, they report an endogenously derived EU power-to-gas capacity of up to 546 GW [97]. Considering that the natural gas import capacity from non-EU countries and LNG terminals currently available amounts to approximately 900 GW, this power-to-gas capacity is substantial.

4.2. Micro-economic conditions for renewable gas production

After having discussed the volume potential of different types of renewable gases to substitute natural gas from a technical perspective, we now turn to the micro-economics of renewable gas production. This is crucial, since actual market penetration of renewable gases will require that they are able to compete with alternatives [98]. In order

to assess to which extent this is and will be the case, we extracted production cost estimates for the different renewable gases discussed in this paper from existing literature (see Table 5). Please note that we understand production costs as full costs that include the cost for production of biogas, its upgrading into biomethane and its injection into the gas network.

Table 5 Overview of production cost estimates for renewable gases (based on [10, 14, 16, 17, 21, 26, 31, 56, 96, 99]).

Source	Ref.	Full cost of production (€/MWh)	Remarks
Biomethane			
Paturska et al.	[10]	46	Consideration of anerobic digestion only
Zappa et al.	[96]	49	Consideration of anerobic digestion only
van Melle et al.	[14]	52	Average cost reflecting both anerobic digestion and thermal gasification
European Commission	[31]	61-68	Average cost; considering anerobic digestion only
Budzianowski et al	[21]	70	Consideration of anerobic digestion only
Papp et al.	[16]	62-94	Cost range reflects different combinations of plant size, plant technology and feedstock
Thrän et al.	[17]	69-94	Consideration of anerobic digestion only; cost range reflects different combinations of plant size, plant technology and feedstock
International Renewable Energy Agency (IRENA)	[99]	84	Average cost for different residues feedstocks in a high-cost environment
Renewable hydrogen			
van Melle et al.	[14]	52	Low-cost excess electricity only
Perner et al.	[56]	50-75	Based on strong economies of scale due to significant increase of global electrolyser capacity; applicable for both production based on low-cost excess electricity in Europe and maximized production in commercially attractive regions outside the EU (for the latter incl. transport)
Van Wijk, A.	[26]	63	Based on baseload production using mainly off-shore wind power
Renewable methane			
Perner et al.	[56]	100-150	Based on strong economies of scale due to significant increase of global electrolyser capacity; applicable for both production based on low-cost excess electricity in Europe and maximized production in commercially attractive regions outside the EU (for the latter incl. transport)

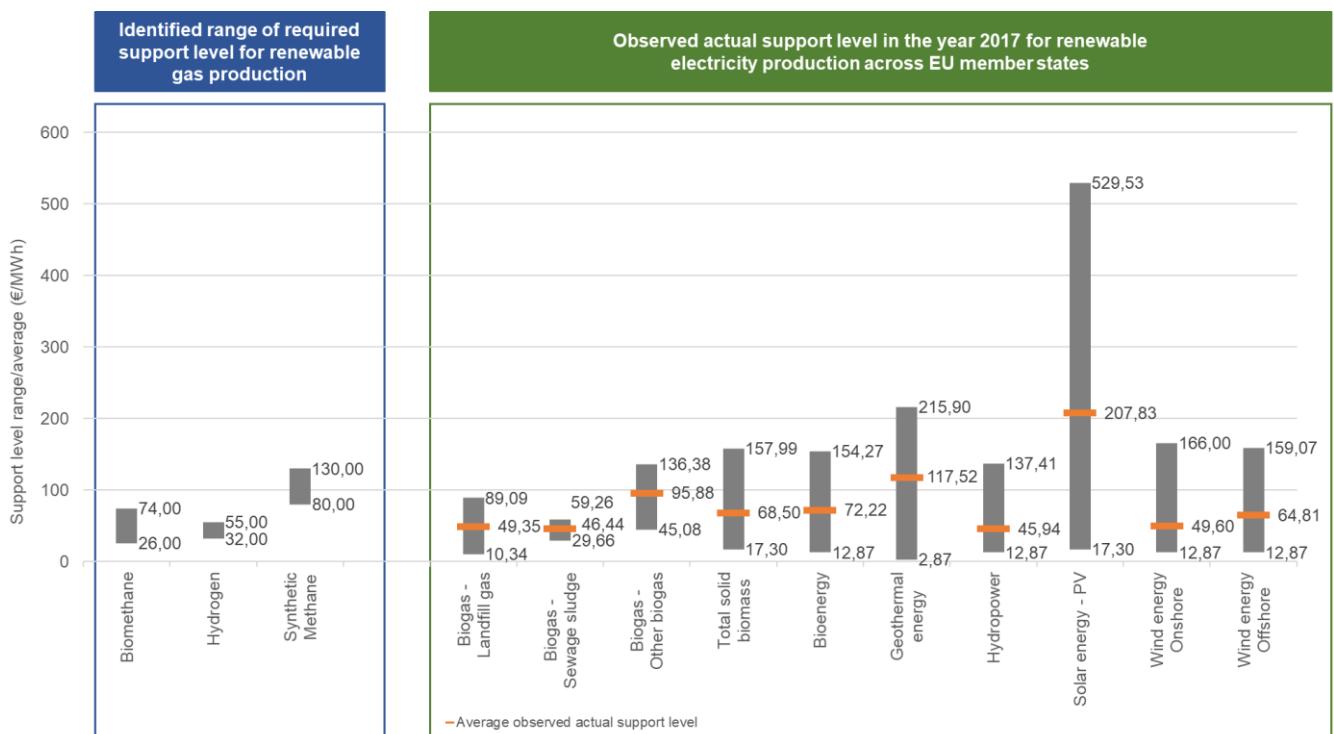
Given the variety of assumptions, technologies, plant sizes, investment cost and conditions, feedstock choices and timelines, both the relative comparability and the general validity of these estimates are limited. However, the overview provided in Table 5 enables an overall estimate of the competitiveness of renewable gases as compared to natural gas. With production costs for sustainable biomethane expected at a level of 46-94 €/MWh, production cost for renewable hydrogen at a level of 52-75 €/MWh and the corresponding costs for renewable methane at a level of 100-150 €/MWh, they all lie substantially above the currently observed average European wholesale price for natural gas (around 20 €/MWh) [100]. If the gas price stays at this level and as long as there is no comprehensive carbon pricing regime, rational economic decisions to invest in major additional renewable gas production can only be expected if backed by effective support to compensate for the premium over the natural gas wholesale price [17, 101, 102]. We empirically examined one such support scheme (see section 3.2 for description and section 4.4. for discussion). For further information regarding renewables support schemes in general, we refer the interested reader to the paper of Kitzing et al., which provides a comprehensive overview of the different policies applied in Europe [103].

The necessity to support scaling-up of renewable gas production with public interventions is one of the major conclusions of the reviewed studies (section 3.1. for details). In addition, some of the studies argue that, considering

the massive transformation required to build a climate-neutral energy system, the natural gas price does not appear to be a proper benchmark for renewable gas production costs in a long-term context. Production costs for renewable gas should rather be compared with renewable alternatives. In addition, for a full picture from a societal perspective, they should be considered in combination with resulting additional costs along the entire energy supply chain [14, 19, 22]. As outlined above, renewable gases can largely be supplied through existing network and storage infrastructure. Massive expansion will be required in renewable gas production, and this hinges on sufficient financial support [20, 101]. This is a situation we observe not only in renewable gas but for the broad majority of renewable energy generation technologies and approaches [15, 62].

The Council of European Energy Regulators recently assessed the level of public support for promoting renewable electricity across Europe [62]. Their results reflect the wide range of generation technologies, support schemes and levels of technical development over more than a decade of public renewable electricity support in the form of feed-in tariffs, feed-in premiums, etc. The aggregated findings of the report are particularly pertinent for assessing the economic competitiveness of renewable gas production. Figure 4 illustrates the range of support required for renewable gas and compares it to actual support levels for electricity as identified by the Council of European Energy Regulators [62].

Figure 4 also illustrates that renewable electricity is receiving substantial support (see green box). The level of this support strongly differs between technologies, both for average and min/max values. If aggregated, the weighted average support level for renewable electricity produced in Europe was 96.29 €/MWh in 2017 [62]. While there are new installations that receive no public support at all, the reported average support level just for new installations put in operation in 2016 is, at 116.56 €/MWh, even higher than the average across all installations in operation [62]. Based on the renewable gas production cost estimates (see Table 5) and the recently observed average European wholesale price for natural gas of around 20 €/MWh [100], support for renewable gas production (see blue box) across the different types of renewable gas needs to be between 26 €/MWh and 130 €/MWh. This indicates that the support granted to most renewable electricity production technologies would be sufficient for renewable gas also.

Figure 4 Estimated support levels for renewable gas and actual support levels for renewable electricity across Europe (based on Table 5 and [62, 100]).

In addition, renewable electricity receives different forms of indirect support that greatly differ between Member States. It ranges from reduced charges for initial grid connection or different self-consumption allowances to priority dispatch of renewable electricity [62]. Renewable electricity in the amount of 9,651 GWh had to be curtailed for redispatch reasons in 2017, and renewable electricity producers had to be compensated for this by compensation payments totaling more than 850 million € [62].

4.3. Societal implications

Curtailment is an example that serves to illustrate why transforming the energy system is not limited to energy production but requires a holistic approach that includes production, network, storage and end-use appliances. Overall, the interplay of various energy vectors and their infrastructure should be optimized in order to secure energy supply while limiting the increase of total energy system costs [14, 19]. We consider this to be critical for the transformation of the energy system. While society increasingly acknowledges the need for action to mitigate the negative impact of climate change, public choice based research postulates that individuals pay more attention to their specific economic short-term development (disposable income, employment, etc.) than to mitigating climate change [104]. Against this background, we use the determined support levels for renewable gas to derive the indicative additional annual cost (AAC) for gas end-users to enable substituting natural gas by renewable gases. The AAC is calculated as follows (see Table 6 for details about the variables used):

$$AAC = \frac{SUL \times TGD \times S}{TN}$$

Table 6 Variables for the calculation of the indicative additional annual cost (AAC).

Variable	Meaning	Source	Remark
SUL	Support level for renewable gas production	Table 5; [100]	Varies from 30 to 130 EUR/MWh, reflecting the broad range of production cost estimates for different technologies
TGD	Total gas demand	[89]	Projected demand for 2030 (2803 TWh)

| S | Share of total gas demand to be covered by renewable gas | – | Varied from 10 to 100%, illustrating the impact of different penetration targets |
| TN | Total number of end-users connected to the gas grid | [26] | Assumption that costs would be equally shared among all 118 million end-users connected to the gas grid (irrespective of type and size) |

Figure 5 AAC per gas end-user based on different support levels and penetration paths for renewable gas (calculations based on Table 5 and [44, 89, 100]).

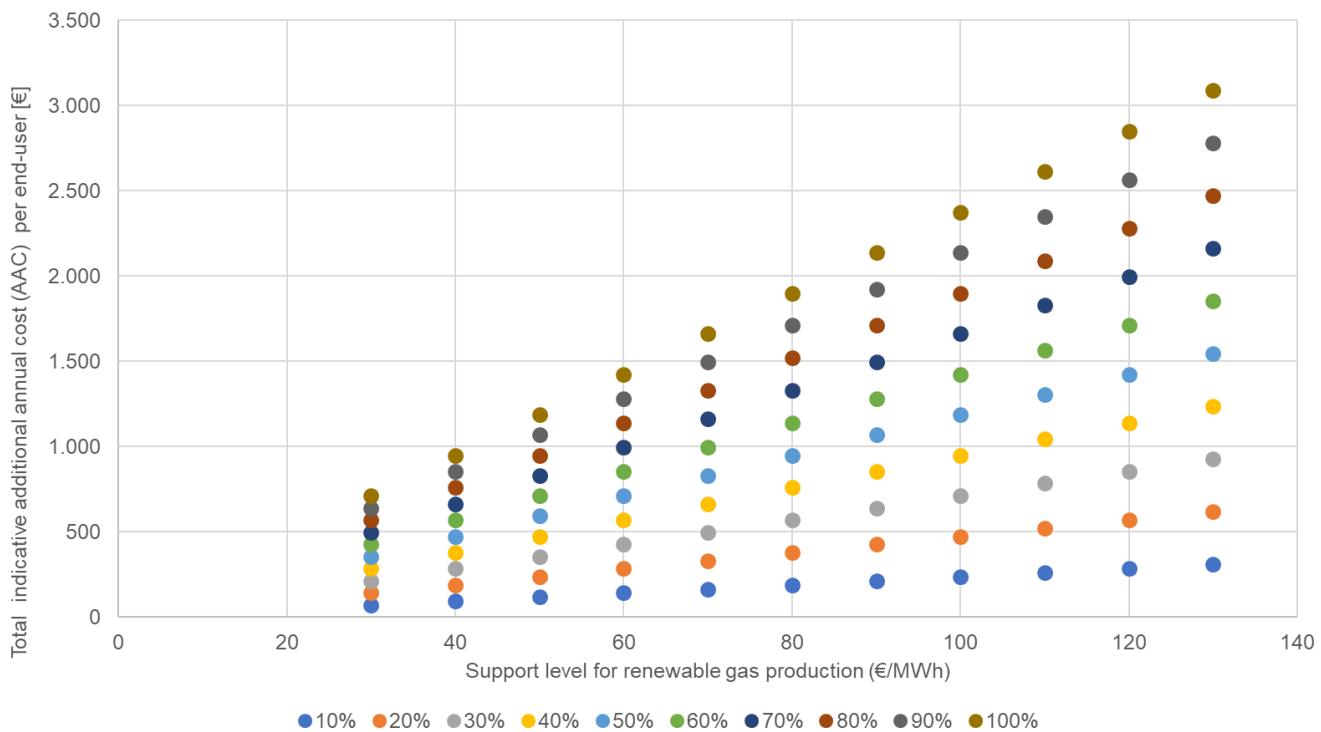



Figure 5 provides an overview of the calculated AAC for different penetration levels of renewable gas substituting natural gas (based on the officially projected demand for 2030, 2803 TWh [89]) and different support levels for renewable gas production. If the costs of the support scheme are equally distributed among all end-users that are connected to the gas grid, the AAC per end-user ranges from approximately € 70 (support level 30 €/MWh; 10% share) to € 3,100 (support level 130 €/MWh; 100% share). Considering that the vast majority of end-users in Europe are households that pay approximately € 1,000 for the 15,000 kWh of gas they consume on average [105, 106], the higher end of the AAC range is out of the question. By way of comparison, if all European gas end-users were to switch their gas supplier (which most have not ever done so far), they could realize an annual savings potential of up to € 400 each [105]. This savings potential matches the AAC for a 50% penetration level of renewable gas that is produced at the lowest production cost reported. Any higher AAC could be expected to impact households' financial situation, possibly affecting public acceptance of the transformation of the energy system in general [77].

In such a situation, utility-maximizing politicians might face opposition for environmental and energy policies with the level of ambition required to indeed reach their GHGE reduction commitments [104]. For that very reason and in order to facilitate the transformation of the energy system in line with these commitments, it appears crucial to provide an energy policy framework that enables the most cost-efficient future energy system design.

Against this background and according to the reviewed studies dealing with potential gas sector contributions (see section 3.1. for details), the major advantages of renewable gas lie in the reduced investment needs along the supply chain. Existing gas storage can address the strongly increasing need for seasonal balancing, existing gas

networks can reduce the magnitude of electricity network expansion that will be necessary and supplying renewable gas to end-users makes major adaptations on the end-user side unnecessary. One of the studies we reviewed quantifies the resulting societal cost benefits at more than € 100 billion per year at EU level [14]. Other studies with national scope arrive at comparable results [19, 23, 24]. Even though expanding renewable gas production will require substantial public support, this is equally true for most renewable electricity production [62, 102]. Indeed, public support for renewable electricity production has led to doubling its share in total electricity delivered to end-users over the last 10 years to reach 30% in 2016 [107]. Based on that, the support schemes can be considered to have been effective [108]. With regards to efficiency, the weighted average support level for renewable electricity produced across Europe in 2017 was 96.69 €/MWh. Given that in 2017, supported installations generated about 603 TWh renewable electricity, the total public support volume in this specific year was around 58 billion €. For the period from 2005 to 2030, the total public support volume for renewable electricity production is estimated to be 900 billion € [102].

At the moment, the situation of renewable gases is literally the opposite. Public support for renewable gas injected into the gas grid to be supplied to end-users in gaseous form exist in some Member States but is rather insignificant at a European level [17, 31]. The same holds true for the share of renewable gas in total gas consumption in general. Therefore, we complement the discussion of societal implications with a what-if analysis, looking at what would be the effects if the public support provided to renewable electricity production in 2017 were available for renewable gas also.

Figure 6 Comparison of potential support costs for renewable gas with actual support costs for renewable electricity (calculations based on Table 5 and [62, 89, 100]).

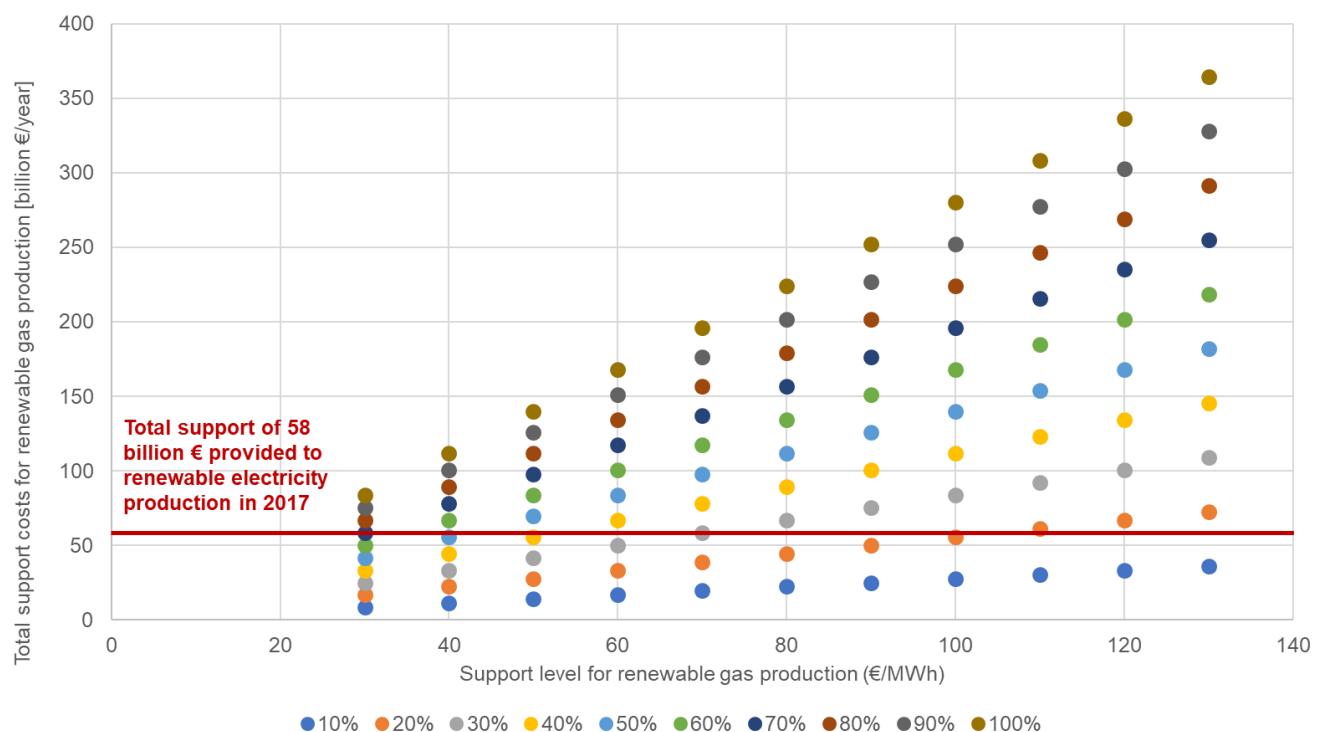



Figure 6 illustrates that an annual support volume of 58 billion € (as granted to renewable electricity in 2017) would enable a renewable gas penetration of 70% in 2030 if that gas is produced at the lowest production cost identified (see Table 5). With average production costs, i.e. an average support level of 80 €/MWh, penetration would be slightly more than 25% and account for approximately 700 TWh of renewable gas production. Compared to the 603 TWh of supported renewable electricity that were produced in 2017 [62], supported renewable gas would mean close to 100 TWh of renewable energy more delivered to end-users, with similar societal costs. This is not

meant to express a preference for renewable gas over renewable electricity; the two energy vectors have strengths in different end-use segments and conditions. Public support schemes for each form of renewable energy should reflect this and, in particular, should incorporate the effects along the entire supply chain, focusing on optimizing total energy system costs.

Beyond these potential cost benefits for society, renewable gases might facilitate public acceptance for this major change and thus contribute to speeding up the transition process towards a climate-neutral energy system as compared to an energy system design without renewable gases. While most of the reviewed studies were prepared or commissioned by organizations close to the gas sector, the study by the industry association of the European electricity industry comes to very similar conclusions, including a substantial level of renewable gas in the energy supply mix [6]. Additionally, similar views have been expressed by the European Commission and the Council of European Energy Regulators. These organizations can be expected to take a neutral stance and aim to optimize the energy supply chain as a whole and across the different energy sources and vectors. Nonetheless, further research could pay special attention to additional views of further energy sector stakeholders.

4.4.   Enabling factors

In addition to the need for a support scheme to improve the business case of renewable gas production for operators and investors [17, 101, 102], our empirical work with focus on the Austrian case delivered a somewhat broader picture of factors for enabling gas sector contributions in an efficient and sustainable way. While these different elements might not be fully applicable or relevant in other EU member states and specific national characteristics could lead to different conclusions, we believe the central observations addressed below have general validity.

Firstly, we identified a substantial difference in the support levels that are required for the different types of renewable gas. According to our empirical results, support levels should take into account the different technology readiness levels of renewable gas production technologies. This is also supported by previous research, which came to the conclusion that technology-specific RES support can create substantial economic benefits [109, 110].

Secondly, even though renewable gas support schemes differ across Europe and generally fall behind support for renewable electricity [10, 17, 31], a support scheme design with feed-in tariffs or premiums whose amount is determined via auctions is broadly in line with recent discussions among scholars and policy makers. Indeed, more and more schemes use market-based instruments, accounting for the fact that auctions allocate scarce funds more effectively [41, 62, 83]. With regards to the support period, research suggests that it should be longer than ten years since it significantly impacts the necessary relative support level and enhances the attractiveness of renewable gas projects for investors [20]. The proposed funding mechanism, i.e. a non-tax support levy payable by gas end-users, corresponds to the most common form of public support currently in place [62]. Considering that the number of gas-end users is only about half the number of electricity end-users [1, 44], but that both energy vectors will need substantial public support to turn renewable, the financial question appears to be particularly sensitive for gas. When deciding how to finance a support scheme, the potential direct social impact in the residential sector [76] and the influence of additional energy charges on the competitive cost position of the industry must be considered [75]. Otherwise, gas end-users might be forced to switch fuels, which bears the risk of creating issues and costs further up the supply chain. This can be expected to hold true for 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 supplying renewable gas to end-users in a cost effective way.

Thirdly, optimizing total energy system costs across renewable energy vectors requires a technology-neutral approach. This has implications for several policy areas. For instance, the European Commission, in its long-term vision towards achieving a climate-neutral economy, attributes a key role to renewable gas in the buildings sector

[31], but the true potential of renewable gas can only unfold if building regulation ensures fair treatment on a par with renewable electricity. Even though renewable electricity-based heat pumps are highly efficient if combined with the right heating system characteristics and energy efficiency standards, renewable gas could be a cost-efficient and quick solution for a large part of the building stock where electrification is facing feasibility and affordability limits [7, 14, 19, 22].

5. Conclusions

Europe's gas sector currently services around 118 million end-users and covers between 20 and 25% of overall European final energy demand. At the same time, EU energy policy makers have formulated the vision of moving into climate-neutral energy supply by 2050, thus saving 75% of total GHGE. Clearly, the gas sector cannot continue with its "business as usual" and its focus on natural gas, but there is the growing realization that a fundamentally transformed gas sector could play a major role in the future. To further home in on this role, we have applied an integrative approach and discussed how, to which extent and based on which prerequisites the gas sector could indeed contribute to an increasingly climate-neutral future EU energy system. We consider the following aspects most important:

- We found convincing arguments that the role of gas need not be limited to balancing volatile RES but that it could also enable climate-neutral energy end-use through the utilization of existing infrastructure in the public domain and on end-user side in a relatively cost-efficient way.
- While the technologies for producing biomethane, synthetic renewable methane and hydrogen exist, actual production volumes are negligible. This need not be the case. According to our review of estimates, there is technical potential to substitute between 11 and 55% of projected total EU gas demand in 2050 with biomethane alone; this corresponds to between 24 and 100% of projected gas consumption by residential end-users. Further work will be required to verify the applicability of such findings for specific national cases.
- The purely technical potential of synthetic renewable methane or hydrogen is nearly inexhaustible, but its effective potential strongly depends on energy system design. Substituting large shares of natural gas with renewable gas seems rather unrealistic if we limit power-to-gas to excess RES electricity, but it appears possible if we factor in imports of renewable gas from low-cost production regions.
- Production cost estimates are in a range of 46-94 €/MWh for biomethane, 52-75 €/MWh for renewable hydrogen and 100-150 €/MWh for renewable synthetic methane. Even though such estimates need to be considered with caution and actual costs differ from case to case, it is evident that production costs are substantially higher than the natural gas market price. Consequently, private investment in renewable gas production can only be expected to reach the levels necessary for a system transformation if backed by an enabling energy policy framework including an effective public support scheme.
- There are strong public support schemes for renewable electricity across the EU. The EU weighted average support stood at 96.29 €/MWh in 2017; for new installations, the reported average was even higher at 116.56 €/MWh. We have calculated that renewable gas would require support levels between 26 and 130 €/MWh, depending on the technology used. This means that the observed support levels for renewable electricity would generally be sufficient for renewable gas also.
- Such support schemes are usually financed through levies on end-users. The additional costs to end-users that would arise from the support levels necessary and high renewable gas penetration rates might run into public acceptance risks. We argue that a 50% renewable gas penetration rate at low production costs could be acceptable for end-users without having to compensate in other areas. This would enable about 1400 TWh/a of renewable gas (as compared to a total renewable electricity production of around 600 TWh in 2017, with a higher absolute level of public support).

- To ensure an energy system transition that allows for achieving climate targets, policy makers need to aim for an optimized interplay of various energy vectors and their infrastructure along the entire supply chain. This is important to maintain safe and secure energy supplies while limiting the increase of total energy system costs. The societal cost benefits at EU level related to renewable gases, continued use of existing gas assets, reduced electricity network expansion needs and redundant adaptations on the end-user side could be beyond 100 € billion per year.
- To realize such benefits, a level playing field for renewable gas and electricity should be established across policy areas. Public support for renewable gas production should reflect the development stages of different production pathways. Support schemes should be market-based and provide sufficiently reliable and attractive investment conditions.
- Allocating support costs to end-users via levies needs to be approached with caution. Gas end-users should not be pushed into fuel switching if this creates issues further up the supply chain, thereby increasing total energy system costs in the long run. Together with the notion of public acceptance for energy transition in general, this represents an important avenue for further research.

List of abbreviations

AAC	Average annual cost
CO2	carbon dioxide
EU	European Union
€	Euro
GHGE	greenhouse gas emissions
km	kilometers
RES	renewable energy sources
SMEs	small and medium-sized enterprises
MWH	megawatt hour
TWh	terawatt hour

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

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.

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Authors' contributions

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

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Endnotes

[a] Comparing these 118 million end-users connected to the European gas grid with 260 million end-users [1] of electricity (which we consider a necessity for any household or business) shows that across Europe approx. 45% of all European end-users are connected to the gas grid.

[b] The Austrian legal framework stipulates that social partners such as the Chamber of Labour, the Chamber of Commerce, the Chamber of Agriculture and the Federation of Austrian Industries have party status in proceedings of the Austrian regulatory authority for electricity and gas [3]. Therefore, representatives of these institutions were involved in the discussion process to bring in their respective views already at an early conceptual stage.

[c] 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 [5]. The European association of the electricity industry even expects a level of direct electrification of 38-60% [6]

[d] 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 [7].

[e] In case of on-site use of raw biogas solely for electricity production (typically the case if there is insufficient local heat demand, which can easily be the case in rural areas), only up to 35% of the gaseous energy are utilized. If the biogas is upgraded to biomethane and injected into the gas grid various end-uses with efficiencies up to 90% and more (e.g. domestic gas-fired heating system) are possible [10, 11].

Table 1

Title	Author	Year	Geographic scope	Sector(s) covered	Main conclusions	Ref.
Gas for Climate – How gas can help to achieve the Paris Agreement in an affordable way	van Melle, et al.	2018	EU	Buildings, electricity, industry, heavy duty transport	- Renewable gas production capacity in the EU can reach a significant level by 2050. - A future energy system including renewable gas shows substantial cost savings compared to a system without renewable gas.	[14]
Decarbonization Pathways	Eurelectric	2018	EU	Buildings, electricity, industry, transport	- A future energy system characterized by strong direct electrification (up to 60% of total demand), energy efficiency and further non-emitting allows to reach 95% GHGE by 2050. - Despite a limited role of biomethane, particularly synthetic renewable gas plays a significant role (indirect electrification).	[6]
A 100% renewable gas mix in 2050?	Bouré et al.	2018	France	Buildings, industry, transport	- Renewable gas (combination of biomethane and synthetic methane) could fully reduce natural gas by 2050. - The projected production costs for renewable gas are comparable to those for renewable electricity generation within a 100% renewable electricity scenario.	[15]
Energiemarkt 2030 und 2050 – Der Beitrag von Gas- und Wärmeinfrastruktur zu einer effizienten CO2-Minderung (Energy market 2030 and 2050 – The contribution of gas an heat infrastructure to an efficient CO2 reduction; authors' translation)	Hecking et al.	2017	Germany	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.	[18]

Der Wert der Gasinfrastruktur für die Energiewende in Deutschland – Eine modellbasierte Analyse (The value of German gas infrastructure – A model-based analysis; authors' translation)	Bothe et al.	2017	Germany	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.	[19]
Green Gas Potential in ONTRAS Network Area	nymoen|strategie-beratung	2017	Germany (regional)	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.	[22]
Riesiges Potential an grünem Gas (Huge potential of green gas; authors' translation)	Papp et al.	2017	Austria	Buildings	- Renewable gas production 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.	[16]
Kalte Dunkelflaute – Robustheit des Stromsystems bei Extremwetter (Dark doldrum – Robustness of the electricity system during extreme weather; authors' translation)	Huneke et al.	2017	Germany	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.	[23]
Klimaschutz durch Sektorkopplung - Optionen, Szenarien, Kosten (Climate protection trough sector coupling – Options, scenarios, costs; authors' translation)	Ecke et al.	2017	Germany	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.	[24]
Erneuerbare Gase – Ein Systemupdate der Energiewende (Renewable gases – updating energy transition; authors' translation)	Klein et al.	2017	Germany	Heat, industry, feedstock, transport, electricity	- The achievement of the 2050 climate targets is only possible with a future energy system design that includes the gas infrastructure and a significant level of renewable gas. - This will also realize substantial cost savings compared to a scenario without a significant role of the gas sector.	[25]

| The Green Hydrogen Economy in the Northern Netherlands | van Wijk | 2017 | Netherlands (regional) | Industry, feedstock, transport | - The currently widely natural gas based large-scale chemical industry cluster in the Northern Netherlands shall be transformed to a hydrogen economy by around 2030.
- This is based on a massive development of especially wind and power-to-gas capacity and retrofitting natural gas pipelines to transport pure hydrogen. | [26] |
| H21 – Leeds City Gate | Sadler et al. | 2016 | UK (regional) | Heat, industry | - The gas distribution system in the city area of Leeds (approx. 6 TWh annual consumption) shall be converted to 100% hydrogen over a three-year period.
- Hydrogen is produced through traditional steam methane reforming of natural gas delivered as usual through the transmission system.
- The carbon dioxide is sequestrated deep under the North Sea. | [28] |