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

Christian Lebelhuber (Energy Institute at the Johannes Kepler University Linz / Altenbergerstraße 69, 4040 Linz, Austria / christian.lebelhuber@jku.at
Horst Steinmüller (Energy Institute at the Johannes Kepler University Linz / Altenbergerstraße 69, 4040 Linz, Austria / steinmüller@energieinstitut-linz.at)

Abstract

Background: Mitigating climate change requires fundamentally redesigned energy systems where 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 policymakers.

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 may 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 technical potential to substitute major parts of natural gas with renewable gas of biogenic and synthetic nature. While this will require public support, we observe this requirement in a comparable magnitude also for renewable electricity.

Conclusion: Given the societal benefits and the competitiveness of renewable gas as compared to renewable alternatives, energy policymakers should incorporate renewable gas and the existing gas infrastructure in the overall energy system framework. The objective should be an optimized interplay of various energy vectors and its infrastructure along the entire energy supply chain. This requires a level playing field for different renewable technologies throughout 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 realistically higher costs for end-users.

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

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 the one of Wall et al. or Götz et al. dealing with renewable gas production pathways [8, 9]. The technical potential of these production pathways has also already been addressed by Baldino et al., Scarlat et al. and others [12, 13]. On the commercial side, e.g. Paturska et al., Thrän et al. and Papp et al. have dealt with micro-economic conditions for renewable gas production under different settings [10, 14, 15]. While the scholarly discussion of renewables support policy is currently focused on electricity, the papers of e.g. Budzianowski et al. and Repele et al. provide, by contrast, some findings specifically for renewable gas [16, 17]; at least from a theoretical perspective. Beyond that, there are various studies prepared or commissioned by academic but also industry organizations close to the gas sector that outline the potential and economic benefits of renewable gas for different geographic scopes, different energy end use segments and based on different assumptions with the presumed aim to raise awareness for these aspects among energy policymakers [18–20, 24, 25].

Missing, however, is an integrative approach that brings together these various research streams to critically discusses 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 [28]. Simply spoken, this requires cutting GHGE by half in each decade to come [29]. However, since the European Union has committed itself to meet the objectives of the Paris Agreement [30] adopted in 2015, the need for even stronger efforts evolved. Consequently, the European Commission prepared in 2018 a new long-term vision to achieve a climate-neutral economy with net-zero GHGE by 2050 [31]. In this context 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, and (iii) sequestering carbon dioxide for permanent storage in geological underground formations [31].

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 [32]. 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, 33, 34]; this translates into the policy objective of reducing final energy demand by 20% by 2020 [35], and by 30% by 2030 [36]. 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 [31]. This includes natural gas. Consequently, 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 that the share of renewable energy shall reach at least 32% by 2030 [37].

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 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 [38]. This, however, has been relativized by a study of the industry association of the European electricity industry which expects in the most progressive scenario electrification to 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 [39]. This was reconfirmed by the European Commission's long-term vision for climate-neutral economy which was published in 2018 and portrays an energy system integrating the various energy vectors such as electricity and gas [31]. 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 [32]. These include a finely meshed network that connects 118 million end-users[a] within the Union [42], comprehensive storage infrastructure, and the potential to substitute natural with renewable gas [32]. 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 5).

Half of the studies in the sample (see

Table 5).focus on Germany, where the extensive “Energiewende” (energy system transformation) 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 situation, and which arrive at similar conclusions.

Publications in academic journals that would be relevant for this 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 1) and deliver on the discussion of technical potentials and micro-economic cost aspects of renewable gas.

Table 1: Articles about specific aspects used to enrich the review sample

Aspect	References
Statistics and databases	[4, 44–47]
Renewable gas production technology	[8, 9, 49–54]
Technical potentials	[10, 13, 55]
Economic considerations	[15, 56, 57]
Legal/regulatory background	[31, 32, 36, 37, 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]. Comparable processes will also have to be set up in other countries, since the revised Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources requires member states to adopt national renewable energy action plans by 2020 [37].

Table 2: Details of focus group sessions 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 the economy and society as a whole, without particular focus on the gas sector. The four discussion sessions that took place (see Table 2 for details) were prepared and moderated by the Energy Institute at the 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 [18]. 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 this causes [31].

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 [45]. 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, according to a considered study they will not reach competitive investment cost levels by 2050 [18]. And even if they do, their self-discharge characteristics limit their potential for seasonal storage [18, 24]. However, considering the long-time period until 2050 and intensive research efforts, this assessment might change over time.

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 [46] 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 disposes of large volumes of linepack and can manage substantial pressure differences [6]. Consequently, it is easier to balance as electricity networks and bears a lower risk of end-user supply disruptions [58].

Gas networks can reduce the need for electricity network expansion: Recent electricity network expansion plans have faced difficulties [78] and involve large investments [18, 19, 79]. Further adapting the network to RES and an increased electricity demand will require further expansions at substantially larger scales [6, 18, 21]. 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 [18, 20, 21, 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 [18, 19, 24].

Replacing natural gas by renewable gas enables climate-neutral energy end use: The reviewed studies 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 [15, 18, 24].

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 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, a decentralized, local biomethane production could support the achievement of this objective [18, 25]. This would also create new jobs and strengthen the rural economy [8, 18].

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, 21] 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 [18, 21, 24, 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 as e.g. currently used in the chemical industry [72]. However, in the context of a climate-neutral energy system, to prevent the resulting carbon dioxide from emitting into the atmosphere, it needs to be either permanently utilized or stored [31]. This is planned for the H21 project in Leeds where resulting carbon dioxide shall be compressed and sequestrated deep in the North sea [27]. Another technological perspective for the future production of the 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 to pure hydrogen systems [27], the potential to blend hydrogen into the existing natural gas system is limited to single-digit percentage shares [18, 21, 69]. Higher percentages might require some adaptation of network infrastructure and end use appliances [18, 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, 18, 20, 50, 51].

Beyond the intra-EU potential for the production of renewable gas, there is also the possibility to import renewable gases [18, 20, 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 [18]. 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 [19, 20].

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 for the time being a minor role and public acceptance is low [81, 84]. However, there is the vision and technology that renewable gas develops over time to a relevant substitute of traditional liquid fuels and could help to reduce transport-related GHGE [70]. This is particularly relevant in heavy-duty road transport, where electric drives face technological limits [18, 81]. The buildings sector, on the contrary, is still significantly based on fossil fuels 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, 18, 20, 21]. While often renewable district heating and electric heat pumps are discussed as primary means of reducing GHGE in this sector [18], reviewed studies argue that renewable gas can make a beneficial contribution to a future energy system in this sector [14, 18–20]. Proponents argue that, beyond the economic considerations of building owners in the context of heating system adaptations, a continued use of existing gas infrastructure in the public domain would create added value also for society as a whole [14, 18–21, 23, 25–27]. In the industry segment, the situation is again different. This is particularly due to the fact that there are for the time being technological limitations for the direct use of electricity in high temperature processes [6, 18, 19]. Nonetheless, the European steel-making industry, as 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 [74]. Such research and development could lead to electrification’s technical limitations being overcome over time [73]. Complete open is, however, how this would affect the competitiveness of the European industry on the global market [75]. The situation for gas in electricity is, among others, strongly influences by the intended fade out 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, 23]. To maximize energy efficiency, resulting waste heat could also be used where possible.

<u>Utilization of readily available gas infrastructure requires little investment</u>: Given the fact that the natural gas infrastructure is already in place, deployment of renewable gases can be expected to require no large-scale gas network expansion. Making the gas networks ready for renewable gases and particularly hydrogen will require adaptations. For Germany a study that investigated in detail the cost for these adaptations arrived at the conclusions that this will be at a level of 25% of the replacement investment which are required anyway to keep the capacity of the network [57]. Beyond that, further investments would be limited to connecting a significant number of biomethane production plants and power-to-gas facilities [18]. This, however, would incur only insignificant costs [25]. Another advantage 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 EU borders [20].

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 [18]. 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 [18]. If end-users continue using gas-fired appliances based on renewable gas, this could significantly speed up the transition [19]. The same holds true for industrial processes where alternatives to gas rarely exist or would require lengthy research and transformation processes [6, 18, 19, 24].

A gas sector contribution to a future energy system can mitigate public acceptance issues: We observe that local resistance to large-scale renewable generation capacity construction can be substantial [76]. Also, the overhead lines common in electricity transmission networks are often perceived negatively by the affected local communities [18, 77]. Public acceptance is less of an issue for gas networks, because they are mostly underground [20]. 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 [6, 20, 21]. This contrasts with the gas infrastructure, which is already in place [18, 21].

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 [20, 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 [20, 21]. In particular this is due to the fact that an energy system with multiple energy vectors is less concentrated and therefore more flexible in stress situation [19, 21, 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 [18, 20, 21, 23]. All arguments in favor and against the potential role of the gas need to be factored in when modeling societal cost implications. This should then be the basis for policy making [18, 20, 21, 23].

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 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 € 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 [18]. The expectation of Eurelectric that average annual investment at a level of € 90 to € 110 billion will be required to build up renewable generation and transmission capacity in an electricity-focused system provides [6] some justification for values at such a level.

Bothe et al. and Ecke et al. follow a similar reasoning, estimating societal cost savings in Germany at € 12 billion [20] respectively € 4 billion per year [23] 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 [22].

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 expansions of the electricity distribution network and the advanced utilization of biomethane potentials [24]. This conclusion is supported by nymoen with similar results [21].

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 € 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 [19].

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 [18, 21]. 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, 18, 20]. 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 [24]. 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.

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 [23, 24]. This is especially true where buildings being currently heated with natural gas need to be adapted for heat pumps [20, 21]. 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 [6, 23].

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 [44]. Given the fact that methane is as greenhouse gas several times more harmful than carbon dioxide, this drives global warming beyond proportion [13, 63]. 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 [63]. Replacing natural gas delivered to Europe from distant sources by renewable gas produced within the EU or nearby could improve the situation [44]. A recent study with focus on methods for the determination of methane emissions in EU gas distribution systems determined that below than 10% of total methane emissions of EU member states are actually the result of methane leaks, while the largest causers are the agriculture and waste sector [65]. Nonetheless, against the background of a climate-neutral energy system this issue should be considered with caution. Since in a methane supply chain a certain level of fugitive methane emissions can hardly be inhibited from a technical perspective, the gas sector should set up coherent determination standards and methods to ensure transparency [65] and continue to minimize the level of 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 [18]. 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 [37]. In addition, national measures may additionally 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 [14, 25]. 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 in this subchapter on the specific 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 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 respective considerations and arguments presented, are based on the justified assumption of Papp et al. that the Austrian gas sector could gradually replace by 2050 at least 23 TWh of natural gas through renewable gas [14]. This volume represents around 25% of the current total natural gas demand [47] and allows to cover the entire gas demand of the residential sector. The focus groups concentrated on the changes to the current energy system framework 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 energy market prices at the moment. 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 scheme should especially be based on feed-in tariffs or feed-in premiums over a period of at least 10 years. In order to reflect the recently observable move towards market-based determination of the support levels [37, 62, 83], this should be determined through auctions run by the responsible authority ("auctioning/clearing authority") based on an intended penetration path of renewable gas. This should establish favorable and predictable investment conditions and facilitate renewable gas production to realize the identified potentials. To reflect the different potentials and different technology readiness levels of renewable gas production technologies, the support scheme should differentiate that accordingly.

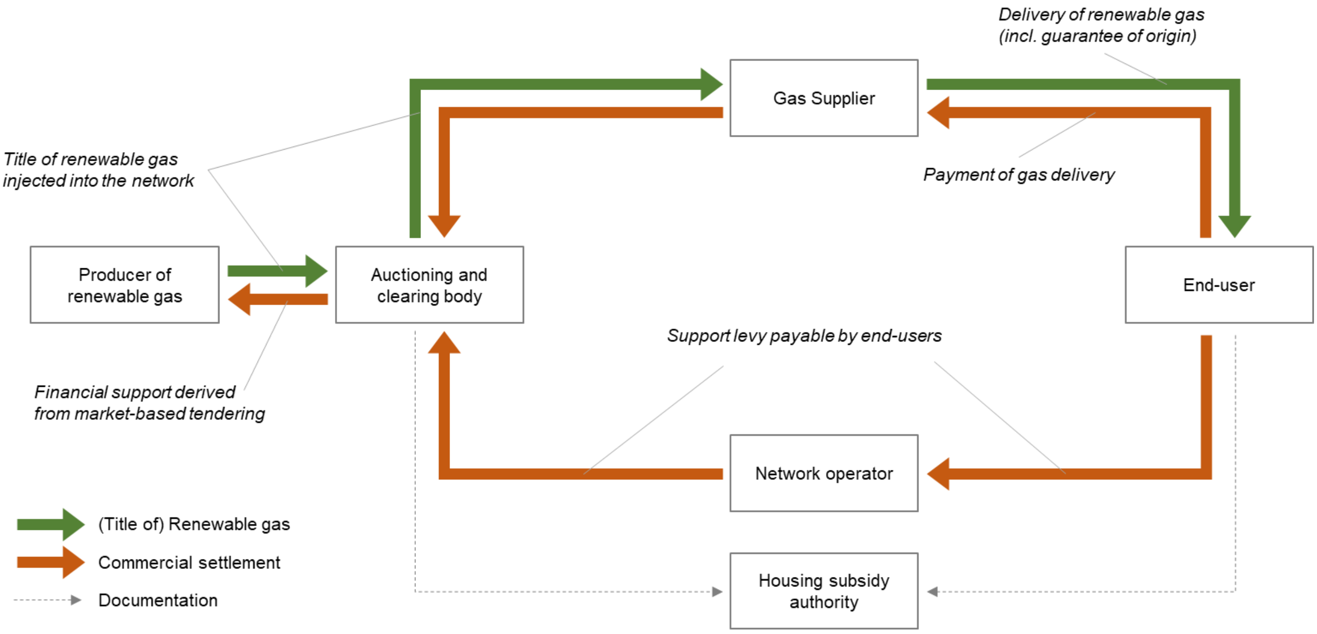
Fair financing of such support instruments: In principle, the support scheme should be financed through a dedicated component of the gas network tariffs that is levied on consumption and payable by gas end-users. Participants considered this to be important to avoid undue cross-subsidies; also, a similar 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 level), 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 is in competition with other (fossil) energy carriers. Therefore, the allocation of cost incurred by the support scheme for renewable gas producers needs to find the right balance between broad socialization and protected of particularly price-sensitive end-users. This is considered as important to maintain competitiveness of businesses and energy affordability throughout the society [75].

Level playing field for all renewable energy vectors on 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 auction and acts as contract partner for renewable gas producers over the entire support period. Additionally, this entity should allocate the ownership title for the volume of renewable gas injected by the producers into the network to gas suppliers. By doing so, priority should be given to the suppliers of gas end-users receiving housing subsidies. The prove of renewable gas consumption by that end-users could either be provided through a direct cooperation between auctioning/clearing authority and the responsible public institution for housing subsidies ("housing subsidy authority") or by the end-user using guarantees of origin provided by its supplier. A guarantees of origin scheme for electricity, gas, heat and cold delivered to end-users needs to be established in any case until mid of the year 2021 [37]. With regards to the commercial settlement, the supplier pays to the auctioning/clearing authority the market price for the received volume. The support levy shall be collected from gas end-users by network operators and transferred to the auctioning/clearing authority to compensate for the support paid to renewable gas producers (beyond the market price). Figure 1 provides an illustration of the described operational handling of such a support scheme.

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. The Northern Netherlands Initiative e.g. aims to build up hydrogen innovation centers to develop technologies, business concepts as well as to educate workforce and society.

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 faded out gradually, energy efficiency measures have to be identified and 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 [31, 32] as well as the industry association of the European electricity industry [6].

However, at the moment renewable gases play a minor role. With 19 TWh biomethane injected to the gas grid by 540 plants in 15 European countries [85] this represents less than 1% of the total EU gas consumptions observed in previous years [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 a broad market penetration does not only require 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 investments into renewable gas production. For this purpose, we discuss in the following the technical potential for renewable gas production and its micro-economic conditions in greater details. Based on that we also pay attention to 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. However, 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 but also support the decision-making of energy policy makers.

4.1. Technical potential for renewable gas production

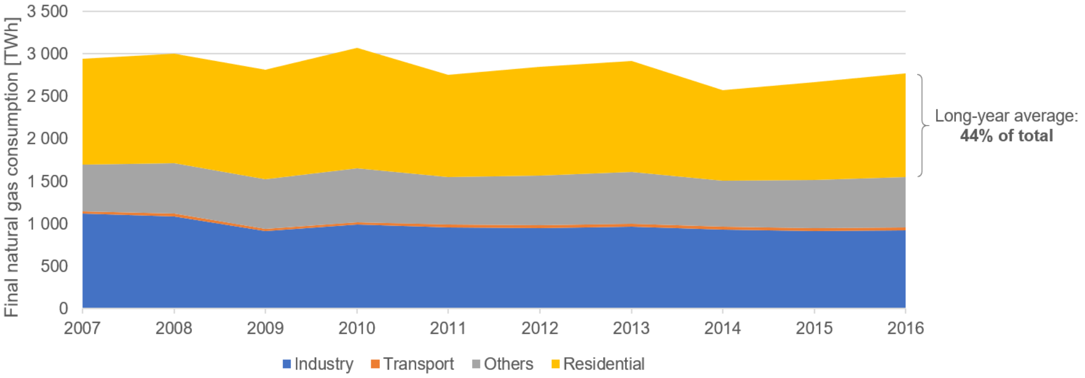
Due to significantly different technological avenues for the production of biogenic and synthetic renewable gas, we differentiate our discussion of potentials accordingly. For biomethane, it needs to be considered that currently the vast majority (89%) of produced biogas is not upgraded to biomethane and injected into the gas network, but used on-site for electricity and/or heat production [40]. This, however, is mainly the results of national support policies incentivizing especially the use in the electricity sector [40].

In its assessment of the potential of biogas in the EU beyond 2020, the European Commission included a scenario of prioritized injection of biogas into the gas grid [40]. For such a scenario, literature provides various arguments such as (i) the replacement of fossil fuels in applications where other renewable alternatives are scarce [40], (ii) the high flexibility value of biomethane due to its easy storage in gas storages and distribution in the gas grid that enables various end uses [12] and (iii) substantially improved end use efficiency[e] of biomethane as compared to an on-site use electricity generation based on raw biogas [10, 11].

For our assessment of the technical biomethane potential we refer to existing literature. It is important to note that we did not consider the absolute amount of biomass residues theoretically available for biomethane production but only considered those volumes explicitly classified as biomethane. Since a biogenic origin itself does not necessarily ensure a sustainable use in a broader context and different concerns related to biogas/biomethane do exist (see section 3.1.2. as well as the papers of Scarlat et al. and Boulamant for further details [12, 88]), the level of detail provided in the relevant literature allowed us to exclude at least potentials being predominantly based on energy crops as feedstock but focus on sewage sludge and residues form the agricultural, forestry, industry and municipal sector. Table 6 provides an overview of the biomethane potentials provided in literature for the years 2030 and 2050. We referenced these potentials to the officially projected EU gas demand for these years [89].

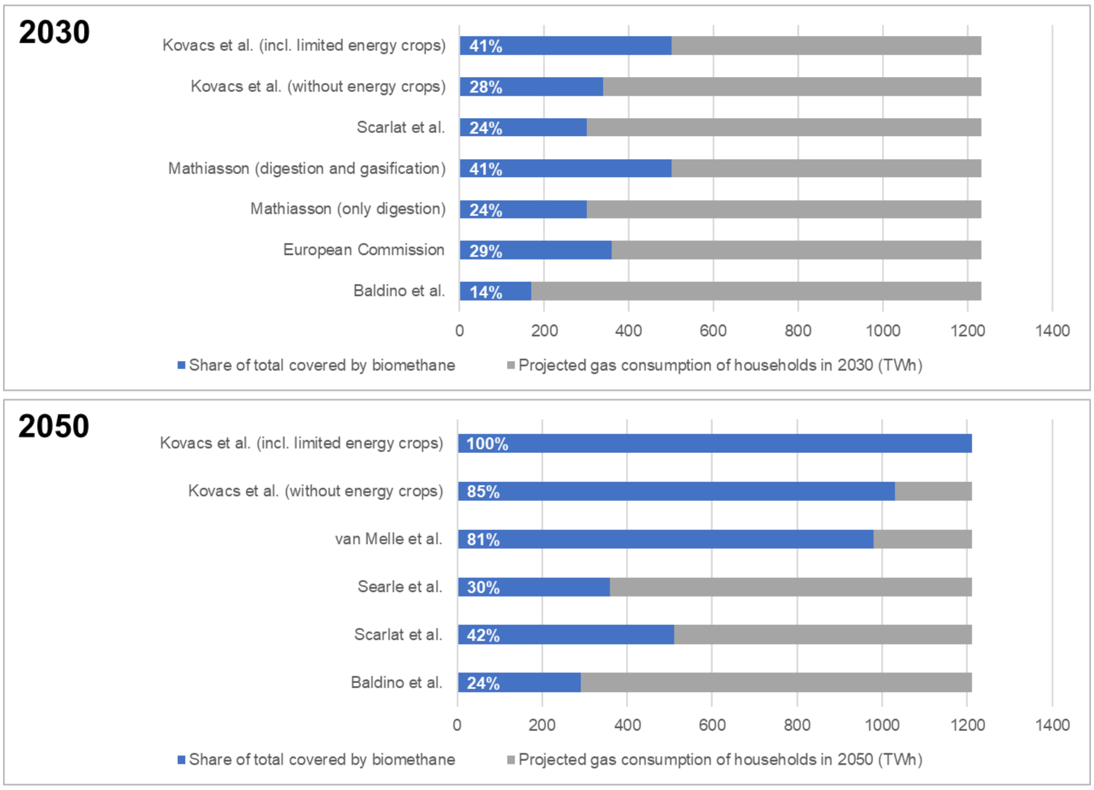
According to the results presented in Table 6, by 2050 biomethane could cover between 11% and 55% of the projected total EU gas demand. In this context however, it is worthwhile to consider the structural configuration of the gas network. The transmission network is operated at high pressure and enables large volume transit, cross-border interconnection and the supply of distribution networks; only the largest end-users (if any) 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, however, are connected to the distribution level and also the injection of biomethane will be predominantly made into the distribution network [90].

Figure 2: Historical EU natural gas consumption per sector; based on [86]



If we assume the 44% long-term average share of the households' gas consumptions in total gas consumption as indicated in Figure 2 also for the projected total gas consumption in 2030/2050 (which is according to official projections for both years only around 10% lower as compared to 2016 [89]), this adds a new perspective which is illustrated with Figure 3. With the technical biomethane potential to be injected into the distribution network by 2050, between 24% and 100% of the projected gas consumption of households connected to the distribution network could be directly covered. Notwithstanding the need for seasonal balancing, this could significantly uncouple the distribution level from gas supplies provided today predominately via the transmission network. While we expect potentially significant national differences which could be addressed by further research on country level, this could indeed be a significant step towards the policy objectives of climate-neutral energy supplies and reduced import dependence [5, 31]. This conclusion coincides with the empirical results presented in section 3.2. which are equally based on a pathway of substituting natural gas supplied to Austrian residential end-users ultimately by renewable gas; being predominantly biomethane [14].

Figure 3: Technical biomethane potentials for 2030/2050 in relation to projected gas consumption of households



With regards to synthetic renewable gas, the assessment of the technical potential follows a different logic, since in contrast to biogenic residues/biomass as feedstock for the biomethane production, solar and wind energy as predominant RES for power-to-gas applications are nearly inexhaustible. Consequently, the pure technical potential for synthetic renewable gas may only be limited by (i) land use restrictions for e.g. wind and solar installations which limit the generation of the required renewable electricity [21, 91, 92], the availability of electrolysers as result of a dynamically growing but still just evolving supply chain [93] and (iii) limitations of carbon dioxide supply in case of renewable methane production [50, 92]. An effective technical potential, however, will rather be the result of the overall energy policy framework for energy system design. 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. [18, 20, 94]. Beyond that there are also structural parameters such as interconnection capacity between markets, the potential for carbon dioxide storage, etc. [94–96]. Consequently, the effective technical potential is case-specific. Blanco et al. in their recent paper just modelled the potential of renewable methane in a widely climate-neutral EU energy system in a scenario-based approach. This allowed to vary key parameters across the 120 scenarios to account for different circumstances as 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]. In comparison with the currently available natural gas import capacity from non-EU countries and LNG-terminals of approx. 900 GW, this derived 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 pure technical perspective, we now turn the focus to the micro-economics of renewable gas production. This is crucial, since even with substantial technical potential actual market penetration will require that renewable gases are able to compete with alternative fuels [98]. In order to assess to which extent this is and will be the case, we reviewed existing literature for production cost estimates for the different renewable gases discussed in this paper (see Table 3). For the sake of clarity, we understand production costs as the cost for production of biogas, its upgrading to biomethane as well as injection into the gas network.

Table 3: Overview of indication production cost estimates for renewable gases

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.	[18]	52	Average cost reflecting both anerobic digestion and thermal gasification
European Commission	[40]	61-68	Average cost; considering anerobic digestion only
Budzianowski et al	[17]	70	Consideration of anerobic digestion only
Papp et al.	[14]	62-94	Cost range reflects different combinations of plant size, plant technology and feedstock
Thrän et al.	[15]	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.	[18]	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 electricity
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)

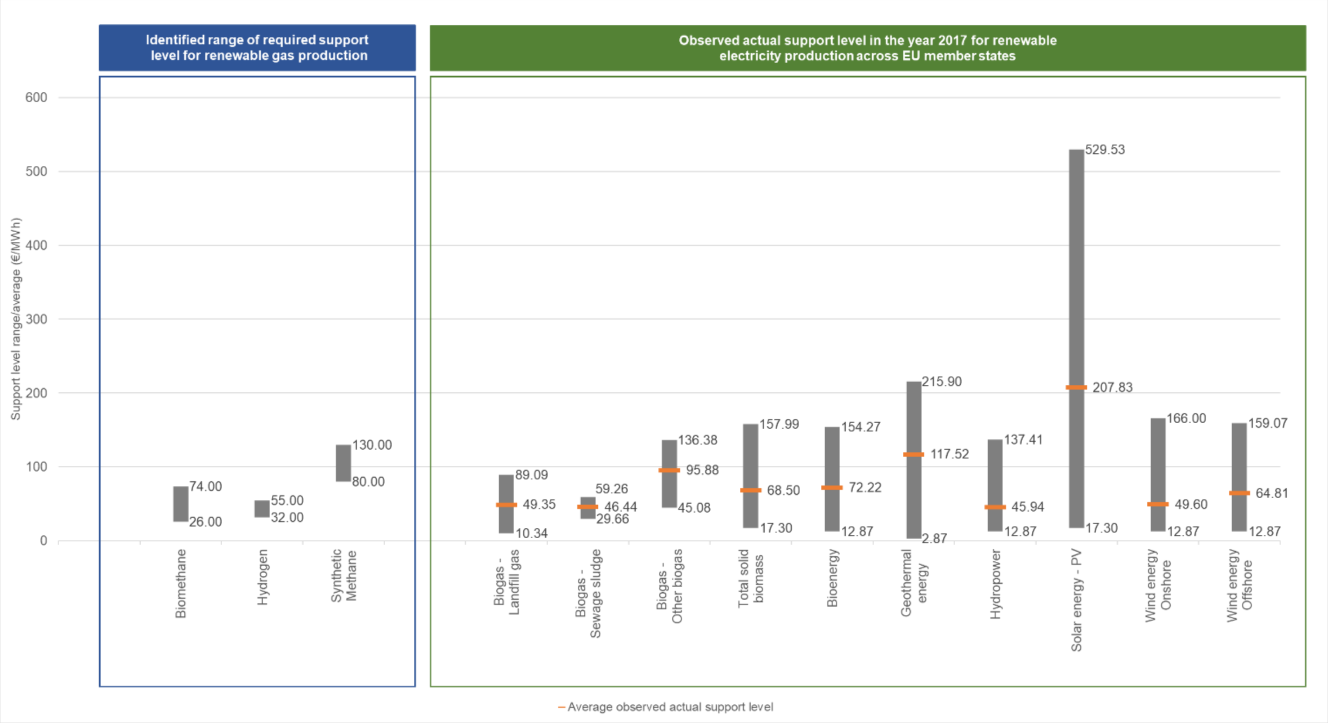
Given the variety of assumptions, technologies, plant sizes, investment cost and conditions, feedstock choices and temporal consideration, both, the relative comparability as well as the general validity of these estimates, is limited. However, the overview provided with Table 3 allows an overall estimate of the competitiveness of renewable gases as compared to the fossil fuel 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]. Consequently, if the gas price stays at such a 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 as compared to the natural gas wholesale price [15, 101, 102]. One such support scheme we have empirically examined and presented in section 3.2. in section 4.4. For further information regarding renewables support schemes in general, we refer the interested reader to the paper of Kitzing et al. that provide a comprehensive overview of policies applied across Europe [103].

For our specific case, the necessity to support the scale-up of renewable gas production with public interventions is also one of the major conclusions of the reviewed studies (section 3.1. for details). In addition, some of the reviewed studies argue, that considering the massive transformation required to build up 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 [18, 20, 21]. In this context, we have already outlined that the supply of renewable gases can be widely based on the use of existing network and storage infrastructure. Required, however, will be a massive scale-up of renewable gas production. Prerequisite for that are sufficient support levels [16, 101]. This, however, is not limited to renewable gas, but applicable for the entire field of different renewable energy generation technologies and approaches in general [25, 62].

The Council of European Energy Regulators has just recently assessed the level of public support related to the promotion of renewable electricity across Europe [62]. While these results reflect the wide range of different generation technologies, support schemes and levels of technical development throughout more than one decade of public renewable electricity support in form of feed-in tariffs, feed-in premiums, etc., in particular their aggregated findings, are of high importance for assessing the economic competitiveness of renewable gas production. Figure 4 illustrates the identified range of the support level for renewable gas as compared to the observed, actual support levels required for electricity as identified by the Council of European Energy Regulators [62].

Figure 4 illustrates that also 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. In aggregate, the weighted average support level for renewable electricity produced across Europe was in 2017 at a level of 96,29 €/MWh [62]. While it needs to be noted that there are also some new installations that receive no public support at all, the reported average support level just for new installations put in operation in 2016, is with 116,56 €/MWh even higher than the previous value reflecting all installations that were in operation [62]. Based on the renewable gas production cost estimates (see Table 3) and the recently observed average European wholesale price for natural gas of around 20 €/MWh [100], the resulting support for renewable gas production (see blue box) is estimated to be across the different types of renewable gas in a range between 26 €/MWh and 130 €/MWh. This indicates that the support levels granted for the majority of renewable electricity production technologies would be sufficient also for the production of renewable gas.

Figure 4: Estimated support levels for renewable gas and actual support levels for renewable electricity across Europe in 2017; based on Table 3 and [62, 100]



Beyond that, renewable electricity is, with great variance between Member States, also receiving different forms of indirect support. This ranges from reduced charges for the initial grid connection, different self-consumption allowances up to priority dispatch of renewable electricity produced [62]. Since in 2017 a renewable electricity production volume of 9,651 GWh had to be curtailed for redispatch reasons, a total compensation payment of more than 850 million € was paid to renewable electricity producers just in this context [62]. With a further growth of particularly volatile renewable electricity capacity, further challenges for network operation are arising [34]. In this context an intensified need for curtailments could be particularly mitigated

4.3. Societal implications

The just addressed aspect of curtailment is an illustrative example that the transformation of the energy system is not limited to energy production but requires a holistic approach including production, network, storage as well as end use appliances. The aim should be to optimize the interplay of various energy vectors and its infrastructure in order to maintain a safe energy supply while limiting the increase of total energy system costs from a societal perspective [18, 20]. We consider this to be a critical issue for the transformation of the energy system. While the society is increasingly acknowledging the need for actions 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.) instead of taking also economic efforts to mitigate climate change [104]. Against this background we use the available production cost estimates for renewable gas (Table 3) to derive indicative additional annual cost (AAC) for gas end-users to cover the substitution of natural gas by renewable gases. This AAC was calculated as follows (see Table 4 for details on the variables used):

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

Table 4: Variables for the calculation of indicative additional annual cost (AAC) for gas end-users related to the substitution of natural gas by renewable gases

Variable	**Meaning**	**Source**	**Remark**
SUL	Support level for renewable gas production	Table 3; [100]	Varied from 30 to 130 EUR/MWh to reflect the broad range of production cost estimates for different technologies
TGD	Total gas demand	[89]	Demand for 2030 (2803 TWh) considered
S	Share of total gas demand to be covered by renewable gas	–	Varied from 10% to 100% to illustrate the impact of different penetration targets
TN	Total number of end-users connected to the gas grid	[26]	Assumption of an equal cost sharing among all 118 Mio. end-users connected to the gas grid (irrespective of its type and size)

Figure 5: Indicative additional annual cost per end-user based on different support levels for renewable gas and different degrees of contribution of renewable gases to the total supply

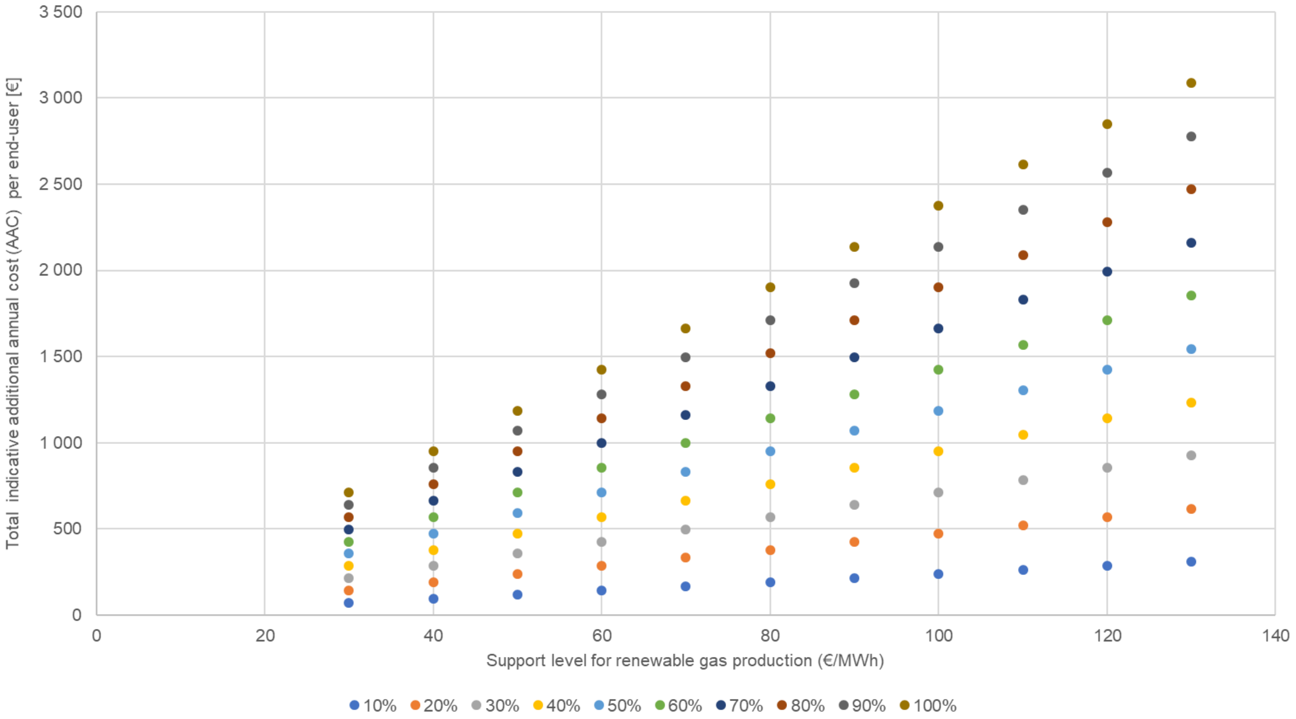


Figure 5 provides an overview of the calculated AAC for different penetration paths of renewable gas substituting natural gas (based on the officially projected demand for 2030 at a level 2803 TWh [89]) and different support levels for renewable gas production. When allocating total costs equally to all end-users connected to the gas grid, the ACC per end-user ranges between approx. € 70 (support level 30 €/MWh; 10% share) and € 3,100 (support level 130 €/MWh; 100% share). Considering that the vast majority of end-users are households with, on European average, total annual cost of approx. € 1,000 for their average gas consumption of 15,000 kWh [105, 106] the upper bound AAC reaches a level which cannot be realistically implemented. However, it is also interesting to note that, for the time being, the majority of European gas end-users has never switched their gas supplier and thus missed to realize an annual savings potential of up to € 400 as a result of intensified competition in a liberalized market [105]. While this savings potential would match with the AAC related to 50% penetration of renewable gas produced at lowest production cost reported, at least any higher AAC bears the risk to cause negative impact. This, in turn, might affect the public acceptance of the energy system transformation in general [77]. Beyond that, there might also be negative effects e.g. for the competitive cost position of the gas-consuming industry.

In such a situation, utility-maximizing politicians might face headwinds when implementing environmental and energy policy 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 allows 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 storages can cover the strongly increasing seasonal balancing need, existing gas networks can reduce the magnitude of electricity network expansion and the supply of renewable gas to end-users prevents major adaptations on the end-user side. A reviewed study quantifies the resulting societal cost benefits to be more than € 100 billion per year at EU level [18]. Other studies with national scope come to comparable results [20, 22, 23]. However, we have already addressed the aspect that the required scale-up of renewable gas production will require substantial public support. Nonetheless it needs to be considered that this is and will be for the foreseeable future equally the case for the major part of renewable electricity production [62, 102]. Due to strong public support of renewable electricity, its share of the total electricity delivered to end-users doubled in the last 10 years and finally reached 30% in 2016 [107]. While the consideration of all energy sectors and a 17% share of renewable energy therein in 2016 demonstrates the need for further major action, the public support can be considered effective in a sense that production capacity was increased substantially [108]. With regards to efficiency, we have already mentioned that the weighted average support level for renewable electricity produced across Europe in 2017 was reported at a level of 96.69 €/MWh. Considering that in 2017 a volume of about 603 TWh renewable electricity was produced by these installations, this results for this specific year 2017 in a total public support of around 58 billion €. For the period 2005 to 2030 the total public support of renewable electricity production is estimated to be 900 billion € [102].

For the time being, the situation for renewable gases is literally the opposite. Since public support for renewable gas injected into the gas grid for supply to end-users in gaseous form does exist in some Member States but is on a European level rather insignificant [15, 40], it is no surprise that this holds also true for the share of renewable gas in the total gas consumption in general. Therefore, we complement the discussion of societal implications with a what-if analysis that assumes the absolute level of public support provided to renewable electricity production in 2017 also for renewable gas.

Figure 6: Total support costs for renewable gas production based on different support levels for renewable gas (see Table 3) and different degrees of contribution of renewable gases to total gas consumption projected for 2030 [89] incl. a comparison with actual total support cost for renewable electricity [62]

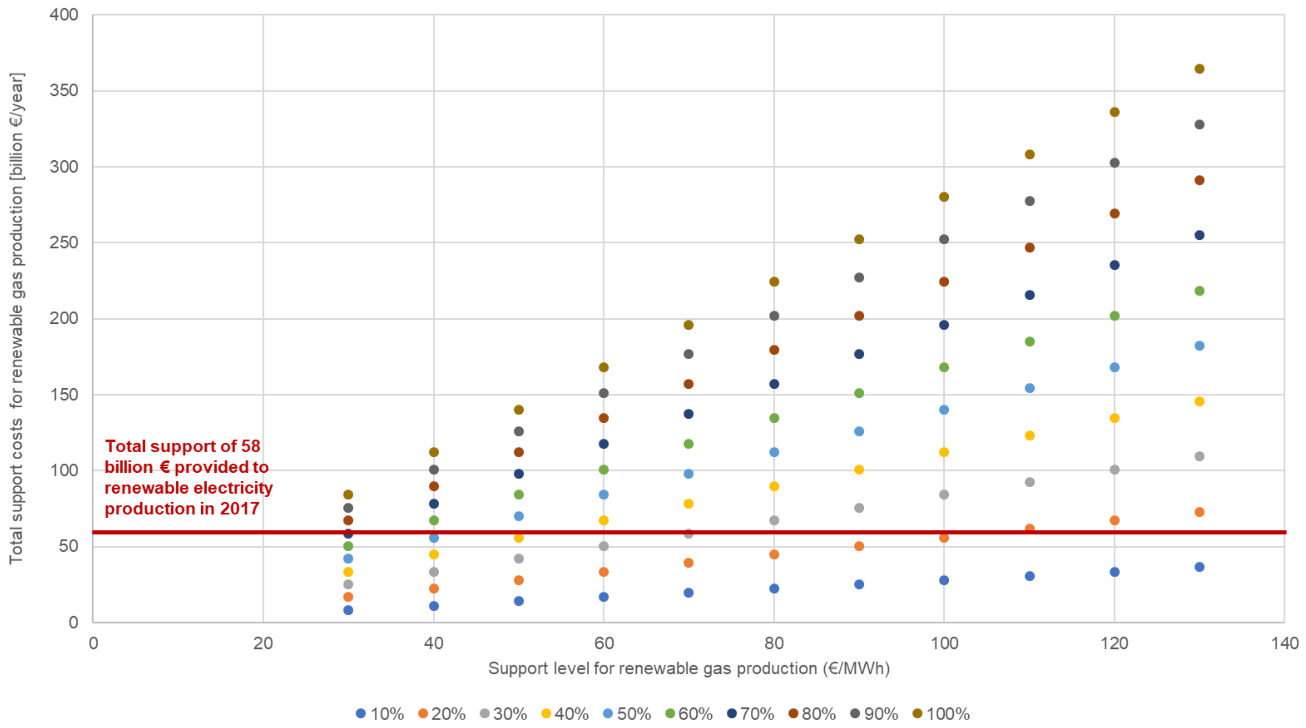


Figure 6 illustrates that an annual support volume of 58 billion € (as provided for renewable electricity in 2017) could be expected to enable a renewable gas penetration of 70% of the total projected gas consumption for 2030 if produced at lowest production cost identified (see Table 3). With average production costs and consequently an average support level of 80€/MWh, the penetration would still be slightly more than 25% of total gas consumption; at a level of approx. 700 TWh. Compared to the 603 TWh renewable electricity produced in the year 2017 based on this public support [62], this would represent roughly additional 100 TWh renewable energy delivered to end users with similar societal costs. This, however, should not express a preference for renewable gas over renewable electricity, since both energy vectors are in different end use segments and conditions superior to any alternatives. Consequently, the allocation of public support for different forms of renewable energy should reflect that. Especially, it should also incorporate the effects along the entire supply chain and focus on the optimization of total energy system costs.

Beyond these potential cost benefits for the 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, also the reviewed study of the industry association of the European electricity industry comes to very similar conclusions that include 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 indeed expected to take a neutral stance with the aim of optimizing 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 already discussed need for a support scheme to improve the business case of renewable gas production for operators and investors [15, 101, 102], our empirical work with focus on the Austrian case delivered a somewhat broader picture of enabling factors to unlock 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 national specifics could lead to partly different conclusions, we believe some central observations addressed in the following are considered to have general validity.

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

Secondly, even though the application of renewable gas support schemes is diverse across Europe and generally lacking behind the renewable electricity support [10, 15, 40], the proposed technical design of the support scheme with feed-in tariffs or premiums for produced renewable gas being determined through auctions is widely in line with the recent discussion among scholars and policy makers. There is indeed a growing use of marked-based instruments and it was identified that auctions allocate scarce funds more effectively [37, 62, 83]. With regards to the support time, previous research suggests that it should ideally be longer than 10 years, since it has significant impact on the necessary relative level of support and enhances the attractiveness of such projects for investors [16]. Also the intended form of compensation of the support volume through a non-tax support levy payable by gas end-users is the most common form of public support [62]. Considering that the absolute number of gas-end users is only about half the number of electricity end-users [1, 42] but for both energy vectors substantial public support will be required, this issue appears to be particularly sensitive for gas. Therefore, when allocating the costs of such 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 in the industry sector must be considered [75]. Otherwise gas end-users might be forced to a fuel switch which create issues and costs further up the supply chain. This can be expected to hold 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.

Thirdly, to allow an optimization of total energy system costs across different renewable energy vectors, a technology neutral approach is required. This has implications on various policy areas. While e.g. the European Commission attributes renewable gas in its long-term vision to achieve a climate-neutral economy a key role also for the building sector [31], the actual potential of renewable gas can only unfold if building regulation ensures a fair treatment alike renewable electricity. Notwithstanding the energy efficiency advantages of renewable electricity-based heat pumps in buildings with the appropriate heating system characteristics and energy efficiency standards, renewable gas could be a cost-efficient and quick solution for the large part of the building stock where electrification is facing its feasibility and affordability limits [7, 18, 20, 21].

5. Conclusions

Europe's gas sector currently supplies around 118 million end-users and covers between 20 and 25% of the overall European final energy demand. Nonetheless, it is highly relevant that EU energy policymakers have formulated the vision to move to a climate-neutral energy supply by 2050; thus saving 75% of total GHGE. While this cannot mean continued "business as usual" for the gas sector with its current focus on the fossil fuel natural gas, there is a growing understanding that a fundamentally transformed gas sector could play a major role also in the future. However, this observation is rather general and requires specification. Therefore, our integrative approach critically discusses 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 also enable climate-neutral energy end use through the utilization of existing infrastructure in the public domain and on end-user side in a, compared to alternatives, cost-efficient way.
- However, while the technologies for production of biomethane, synthetic renewable methane and hydrogen exist, its actual production volumes are negligible. This need not be the case. According to our review of estimates, there is the technical potential to substitute by 2050 between 11% and 55% of the projected total EU gas demand just with biomethane; this could be e.g. sufficient to cover between 24% and 100% of the projected gas consumption of residential end-users. However, further work will be required to verify the applicability of such findings for specific national cases.
- In addition, the pure technical potential of synthetic renewable methane or hydrogen is nearly inexhaustible; its effective potential will rather be a result of the energy system design. While the limitation of power-to-gas to excess RES electricity can hardly be expected to allow major substitution of natural gas, it appears possible with additional 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 will be case-specific, it is evident that production costs are substantially higher than the natural gas market price. Consequently, private investments into the required scale up of renewable gas production can only be expected if backed by an enabling energy policy framework including an effective public support scheme.
- In contrast to renewable gas, there is a strong public support for renewable electricity in the EU. The weighted average support level for renewable electricity produced was in 2017 at a level of 96,29 €/MWh; the value for new installations is with 116,56 €/MWh even higher. The derived support level required for renewable gas is estimated to be across the different types in a range between 26 €/MWh and 130 €/MWh; thus the observed support levels for renewable electricity tend to be broadly sufficient also for renewable gas.
- However, since such support is usually directly allocated to end-users via levies, we identified that the additional end-user costs related to a combination of high support levels and strong renewable gas penetration bear public acceptance risks. Nonetheless, we argue that a 50% renewable gas penetration

at low level production costs could still be acceptable for end-users without the need for compensation in other areas. This would provide about 1400 TWh/a renewable gas as compared to a total renewable electricity production of around 600 TWh in 2017 with a higher level of total public support.

- To ensure the energy system transition in line with climate targets, policymakers need to aim for an optimized interplay of various energy vectors and its infrastructure along the entire supply chain. This is important to maintain a safe energy supply while limiting the increase of total energy system costs. According to reviewed studies the societal cost benefits related to renewable gases, continued use of existing gas assets, reduced electricity network expansion needs and redundant adaptations on end-user side could be at EU level beyond € 100 billion per year.
- To realize such benefits, a level playing field of renewable gas and electricity should be established throughout the different policy areas. In particular, the required public support for renewable gas production should also reflect the specific levels of development of different production pathways. Support schemes should be market-based while providing sufficiently reliable and attractive investment conditions.
- The allocation of such support costs to end-users via levies needs to be made with caution. It should be avoided that gas end-users are pushed to a fuel switch if this creates issues and costs further up the supply chain and thus increases the total energy system costs in the long-run. This notion is certainly an important avenue for further research.

Table 5: Sample of studies reviewed [6, 14, 18–27]

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.	[18]
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.	[25]
Energiemarkt 2030 und 2050 – Der Beitrag von Gas- und	Hecking et al.	2017	Germany	Heat, electricity,	- A future energy system which still comprises gas and heat infrastructure	[19]

Title	Author	Year	Geographic scope	Sector(s) covered	Main conclusions	Ref.
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)				industry, transport	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.	
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.	[20]
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.	[21]
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.	[14]
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.	[22]
Klimaschutz durch Sektorkopplung - Optionen, Szenarien, Kosten (Climate protection trough sector coupling – Options,	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	[23]

Title	Author	Year	Geographic scope	Sector(s) covered	Main conclusions	Ref.
scenarios, costs; authors' translation)					to enable cost savings compared to an energy system design without renewable gas and gas infrastructure.	
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.	[24]
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.	[27]

Table 6: Technical biomethane potentials for 2030/2050 in relation to projected total EU gas demand[1]

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	2803	6%	290	2752	11%	Only sustainable feedstock considered
European Commission	[40]	360		13%	n.a		n.a.	Technological focus on digestion process, gasification out of scope
Mathiasson. (only digestion)	[41]	300		11%	n.a		n.a.	Technological focus on digestion process, gasification out of scope
Mathiasson (digestion and gasification)	[41]	500		18%	n.a		n.a.	Consideration of both digestion process and gasification technology
Scarlat et al.	[12]	300		11%	510		19%	Only residues and sewage sludge are considered; 2050 value represents full technical potential
Searle et al.	[43]	n.a.		n.a	360		13%	Only residues are considered
van Melle et al.	[18]	n.a.		n.a	980		36%	Incl. cover crops based on sequential cropping strategies
Kovacs et al. (without energy crops)	[48]	340		12%	1030		37%	Only residues are considered
Kovacs et al. (incl. limited energy crops)	[48]	500		18%	1510		55%	Additional scenario including most conservative energy crops potential

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.

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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] connected to the electricity network (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 what 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].