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The potential contribution of biogas to the security of gas supply in Germany

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Abstract

Background Germany is highly dependent on natural gas, the availability of which has become uncertain due to Russia's invasion of Ukraine. Biogas provision in Germany is realized by more than 9500 mainly farm-side biogas plants that have the potential to increase the security of gas supply.

Main text To assess the potential contribution of biogas to a secure gas supply in Germany, we combine a literature-based analysis of the current status and potentials of the biogas supply chain with calculations of the marginal costs for producing biogas under the current market conditions. Biogas provided 50 TWh of final energy in Germany in 2021, primarily in the form of power and heat. The production of biomethane, which can in principle replace natural gas when fed into the gas grid, amounted to 10 TWh in terms of the lower heating value, which corresponds to a share of about 1% of the German gas market in 2021. However, at the end of 2021, biogas significantly contributed to the provided power (13 TWh or 22% of power supply from natural gas) combined with co-generated heat (13 TWh or 2% of heat supply from natural gas). Increasing flexible power provision from biogas is promising under the current power market conditions. In contrast, the current biogas substrate mix will lead to crucial limitations: 75% of the input into German biogas are energy crops, which are limited in availability under rising agricultural prices.

Conclusions and recommendations In conclusion, biogas can only make up a small share of the current natural gas consumption. An immediate programme to mobilize the use of biogenic by-products, waste, and cultivated biomass without requiring additional land is recommended. We also propose measures to increase the flexibility of power production and heat use and more greenhouse gas-related incentives of biogas supply for the medium term. Finally, we see the need for additional efforts for non-food feedstock mobilization on a European scale by realizing the envisaged tenfold increase in the contribution of biomethane to a production goal of 35 billion cubic metres by 2030 in the REPower EU Plan of the European Commission.

Keywords Biogas, Biomethane, Gas supply, Ukraine, Nutrition crisis, Energy security

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Background

As of 2021, the German energy supply was based on 15.9% renewable and 84.1% conventional (fossil and nuclear) fuels, referring to the primary energy demand of 3,748 TWh [1]. The acceleration of the "Energiewende" (energy transition) in the beginning of this century led to an increase in the contribution of renewables to electricity consumption of 45%. Fossil fuels still dominate the heat (15.6% renewables) [2] and transport sector (7.5% renewables) [2]. Natural gas, from which 96.8% was

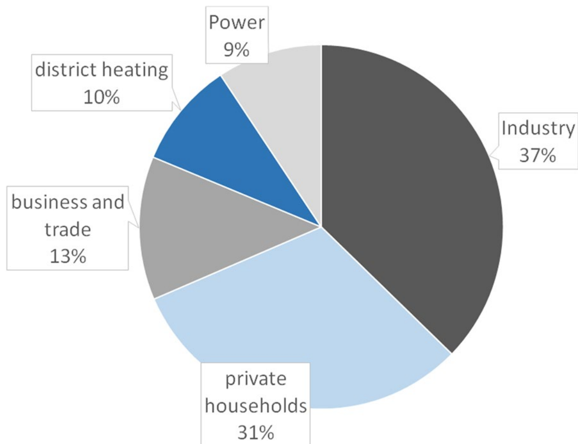

Fig. 1 Natural gas consumption in Germany 2021

imported, became the second largest fossil fuel source for total energy consumption in 2021 [3, 4].

Germany's natural gas consumption (1,012 TWh) covered 27% of the primary energy demand. In 2021, more than half of it was imported from Russia and mainly consumed by industry (373 TWh/a) and private households (312 TWh/a), followed by trade, commerce and services (127 TWh/a), (district) heating and cooling supply (94 TWh/a), as well as power generation (93 TWh/a). In 2022, gas imports from Russia decreased to zero. About 54% of natural gas is used for direct heat generation [1]. The related shares of the different sectors are presented in Fig. 1. The role of natural gas in the energy transition towards net zero was seen as a bridging technology, which was expected to be applied in industrial applications as well as for peak power generation, whereby a combination with carbon-capture and storage (CCS) is also discussed [5].

Figure 2 summarizes the use of bioenergy in Germany in 2019, representing the energetic biomass use as a flow from the resource (biomass from agriculture, forestry and biogenic residues and waste, on the left) through the type of energy carrier (in the medium term) to the use in different sectors (on the right), including export and by-products. The fluxes were calculated following the method described by Thrän in [6], based on data taken from [7]—[8]; where the calculation approach is given in Additional file 1: Annex S1. In 2019, biomass for bioenergy was produced from agricultural (224 ThW), forest resources (130 TWh) and biogenic waste (110 TWh) and used for the supply of solid biofuels (202 TWh), liquid biofuels (127 TWh) and gaseous biofuels (126 TWh), which is mainly biogas. The conversion into gaseous and liquid biofuels was also accompanied by the generation of by-products such as digestate (from biogas production) and press cake or fermentation residues from biodiesel

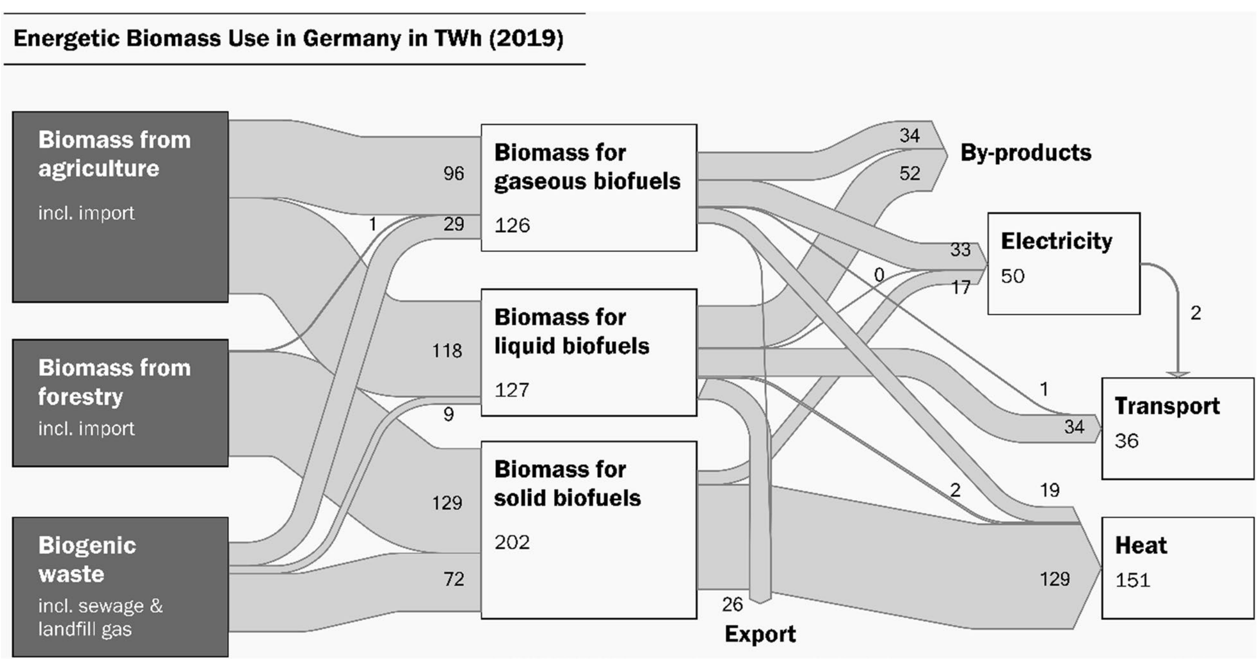

Fig. 2 Energetic use of biomass and the resource-to-bioenergy flows in Germany in TWh in 2019; based on data taken from [7, 8] and the method described by Thrän [9]. The differences between biofuels and final energy / by-products are conversion losses. "Biomass for gaseous fuels" describes the biogas conversion route

and bioethanol production. Biomass contributed to the German energy supply in 2019 with 235 TWh of electricity (50 TWh), heat (151 TWh) and transport fuels (36 TWh; of which 2 TWh were from electricity). It accounts for almost half of Germany's renewable energy production amounting to 527 TWh/a in 2019 [9]. In addition, 26 TWh of liquid biofuels were exported.

Biogas is a renewable gaseous energy carrier, consisting mainly of methane, CO_2 and minor compounds. It is based on biomass from agricultural crops, their residues and other biogenic residues and waste, and is generated via anaerobic fermentation. Biogas is used in all three energy sectors (power and heat generation, transport). It has been part of the "Energiewende" since the 1990s and has been supported for over 20 years under the German Renewable Energy Act (REA) [10, 11]. This law promotes the production of power from biogas by feed-in-tariffs and, since 2017, feed-in-premiums connected with auctions. Both types of subsidy payments result in a certain remuneration level for each kilowatt-hour produced from biogas. The REA reform of 2017 started to combine subsidies with power market revenues via a floating market premium. This is equal to a contract for difference, but does not foresee "negative subsidies" in times when market prices exceed the plants' production costs. In the case of flexible power generation, biogas plants can profit from additional revenues when they perform better than the monthly average of the relevant market price. Based on this public support scheme, today about 9,500 plants in Germany produce and process biogas [12].

Figure 2 also shows that biogas, as well as biofuels, is mainly generated from agricultural biomass and generates relevant by-product streams, amongst which digestate is the main component. Digestate is returned to fields and grasslands for nutrient recycling and humus reproduction. By using agricultural biomass and providing fertilizer, it is much closer interlinked with the agricultural sector than other renewable energies. Notably, the high relevance of prices for agricultural products and land as a key resource for the current biogas production indicates a strong food-energy nexus: when assessing the role of biogas in a secure gas supply, it is important to consider how Russia's war against Ukraine and its changing export policies affect agricultural production as a whole, including the availability of biogas substrates. Grain export reduction is particularly critical at a time when parts of Africa are experiencing the worst drought in four decades, and hunger crises acutely affect other regions [13, 14]. In addition, global mineral fertiliser consumption significantly relies on imports from Russia and the Black Sea region. Hence, Russian influence on international food supply goes beyond the export of crops from this region [15]. Thus, each sound analysis of options for biogas production and use to increase energy security needs to consider both the energy and the agricultural sector.

Alongside this background, this contribution to the debate poses questions about the potential contribution of biogas to the security of gas supply in Germany under resource-related, technical and market constrains and concludes with possible measures on how to secure and expand biogas production under different constraints immediately (within the next 2 years) and in the medium term (up to 2030).

Main text

Methods

To answer this question, we combined a literature-based analysis of the current status and the potential for increase of the German biogas production with a calculation of the marginal costs for farmers producing biogas under fixed feed-in tariffs and those who produce in a flexible mode closer to the market conditions. This includes the following steps.

Analysis of the status quo of biogas and discussion of additional future supply to different German energy sectors

In regard to the current contribution of biogas to the gas security in Germany, we summarize publicly available official statistics concerning energy production and consumption. The status quo is then compared with the current relevance of natural gas in the German energy system under the consideration of the technical requirements for biogas to be used as a substitute. For the discussion of further potentials of flexible biogas, biomethane and related heat production in 2030, we rely on the existing data regarding alternative biogas substrates, the political framework and literature. Potentials for alternative substrates are found in the publicly available residues and waste resources database of the DBFZ [16]. Expectation on flexible power generation relates to the ongoing process of a respective upgrade of most of the existing plants. This corresponds to the current political framework, which includes a mix of flexibility requirements and incentives for all new plants as well as existing plants extending their remuneration period [10]. Also, different studies indicate a potential for excess heat utilization of about 2.1% of residential heating [17] or 2.5% of the CO2 of residential buildings [18] with the distance to the next heat sink as a main limitation. As to the potential of biomethane in 2030, we refer to the existing estimations by Matschoss et al. [19], who selected the existing convertible biogas plants in Germany indicating promising economic characteristics such as a sufficient capacity, pooling options and a limited distance to the gas grid [19].

Assessment of the impact of higher agricultural prices on biogas production

Both global problems in food security and possible fertilizer shortages affect the prices for crops and thus the availability of substrates for biogas production. To assess this food-energy nexus, we used a simplified economic approach following the hypothesis that farmers decide to use land for energy or food & feed production economically based on the expected revenues for both alternatives. Revenues from biogas production for energy are still dominated by public subsidies from the REA, which are still the only or dominant source of income for the majority of biogas plants. Revenues for food and feed production are largely determined by market prices, which are much more directly determined by the ongoing crisis and show large amplitudes in 2022.

To assess the influences of current market events on biogas production in Germany, we calculate the (1) maximum energy crop prices payable for a biogas plant operating under the REA feed-in tariff in order to cover not only its costs but also (2) the attractiveness of energy crops for biogas compared to food & feed crops in a two steps approach:

We compute power provision costs of a typical inflexible German biogas plant with different energy crop input prices and compare them with typical remuneration levels for power from biogas given under the REA. This leads to maximum energy crop prices payable for a plant depending on the plant scale, Capex, Opex and the feedstock mixture under the given assumption without additional revenues from flexible power generation.

These maximum energy crop prices were subsequently compared with those of other agricultural production systems with the gross margin in €/ha as a reference value. The target value is the marginal price of the crop considered. The marginal price of a specific crop is the price at which it generates the same gross margin as the energy crop (silage maize in this example). If this price is reached, the energy crop reaches the economic viability threshold and is no longer the sole best use of the scarce production factor of land.

The assessment is done in a generalized approach (average value) for a typical German biogas plant, which was derived from the DBFZ biogas plant database [20] as the base case, and the calculation was performed using maize silage as the most relevant energy crop and winter wheat and grain maize as competing crops for other agricultural production systems. There are also other calculation models available, i.e. [21–23], but they do focus on more specific cases and not on the typically installed biogas plant. The decision-making for a specific plant is a matter for case-by-case analysis, considering certain substrate mixes, substrate production or price conditions, etc., which are not included here. In particular, lock-in effects are not considered here. It can be assumed that due to the expiry of the REA remuneration for most plants between 2029 and 2032, these effects will have little relevance for decision, as most plants are on their technical end of life. The detailed method and input data for the assessment are described in comprehensive detail in Additional file 1: Annex S2.

Impact assessment of higher prices as well as price volatility for power from biogas plants

Biogas producers who are not producing solely under the REA, can benefit from higher energy prices and increased energy price volatility in two ways. First of all, the recent construction of the floating market premium, without the option of negative values, leads to the effect that if the market price exceeds the individual feed-in tariff, plant operators receive the actual market price instead of just their fixed tariff. Figure 3 presents the daily averages in 2022 compared to a benchmark level for the assumed feed-in tariff. For all days with higher prices, the plant can gain the average market price instead of the feed-in tariff. This is also valid for single hours, which were not shown here to keep the figure uncluttered.

Regardless of the total price level at the power exchange, flexible biogas plants can benefit from price volatility by focusing their power generation to the most expensive hours of one day. In this way, the plant can reach a power price above the average price level, which was the reference for calculating the floating market premium. Additional revenues via price-driven operation depend mainly on the power quotient (PQ), which describes the ratio between installed and rated capacity and is equivalent to the inverse value of daily runtime per 24 h. The potential extra earnings were limited by restrictions such as the available amount of gas storage, heat supply obligations and the revenue share for power market aggregators, because most plants do not reach the minimum capacity to participate in the spot market directly.

In contrast to the impact of higher agricultural prices, the assessment of higher or more volatile power for power supply, i.e. the assessment of a typical flexible biogas plant does not make sense. Hence, we will demonstrate the development of price spread on the power market since the gas crises started and discuss its effects in a qualitative way.

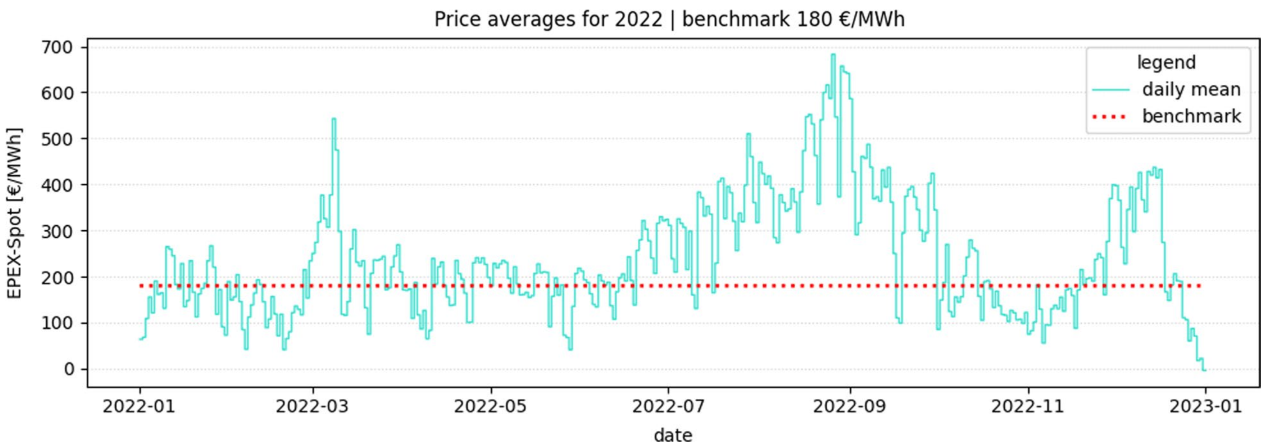

Fig. 3 Daily price averages for the day-ahead market at the power exchange bidding zone Germany + Luxemburg [24]

Discussion of options to increase the contribution of biogas to a secure gas supply

With the assessments of the impact of higher agricultural prices on biogas production and power from biogas plants, we determined uncertainties for existing biogas plants under different remuneration schemes, but also presented ways to circumvent them.

To bring those different aspects together, we finally discuss the results to:

(1) propose robust pathways for further biogas development in Germany and
(2) evaluate Germany's possible contribution to REpowerEU.

Results

Current contribution of biogas to the security of gas supply

The production of (raw) biogas in Germany amounts to 94 TWh/a (primary energy content) [25]. It provided about 50 TWh of final energy in 2021 [26].

The different applications are shown in Fig. 4: the biogas is predominantly used in combined heat and power units (CHPU); typically, in raw form with a methane content of about 50–75% in plants located on farm sites.

Natural gas can be replaced 1:1 by biogas if the latter is upgraded to biomethane. In this case, it can be fed into gas networks and thus made accessible to all areas, in which natural gas is used. This is currently the case in about 230 of the more than 9,000 biogas plants, with an output of about 10 TWh of biomethane [27]. Thus, biogas and natural gas do not have the same application: while natural gas is mainly used for the generation of heat, for heat-driven CHPUs, for the flexible provision of power and for material uses (e.g., the production of fertilizers), biogas is mainly converted to power and heat in CHPUs with constant power generation. To date, only about one-third of Germany's biogas plants meet the technical conditions for flexible power generation [28].

For additional substitution of natural gas, therefore, three biogas options can be considered in the short-term: (a) increasing heat use in CHPUs; b) flexible power production or (c) upgrade to biomethane and feed into the gas grid.

(a) Heat from biogas is mainly generated in combination with on-site power generation; solely heat generation from biogas is not established. The heat extracted is used directly on site or fed into local heating networks. The increasing flexibility of power generation from biogas is usually combined with heat storage and therefore does not limit the use of heat in the future. The volume of currently generated heat amounted to 13 TWh/a [26], which corresponds to about 2% of the heat from natural gas (approx. 550 TWh/a) [29].
(b) Regarding power, total generation from biogas amounted to 28 TWh in 2021 [26], which corresponds to about 6% of Germany's power demand (562 TWh in 2021) [30]. However, as already mentioned, only one-third of on-site biogas power generation plants operate in a flexible mode, i.e. power is provided when power is scarce and therefore expensive, leading also to the use of flexible gas-fired power plants. Flexible biogas plants currently provide 13 TWh/a of power (own calculation based on [29]), which is about 22% of power from gas-fired power plants (use of natural gas for power generation amounted to about 60 TWh/a in 2021) [own calculation based on [29]].

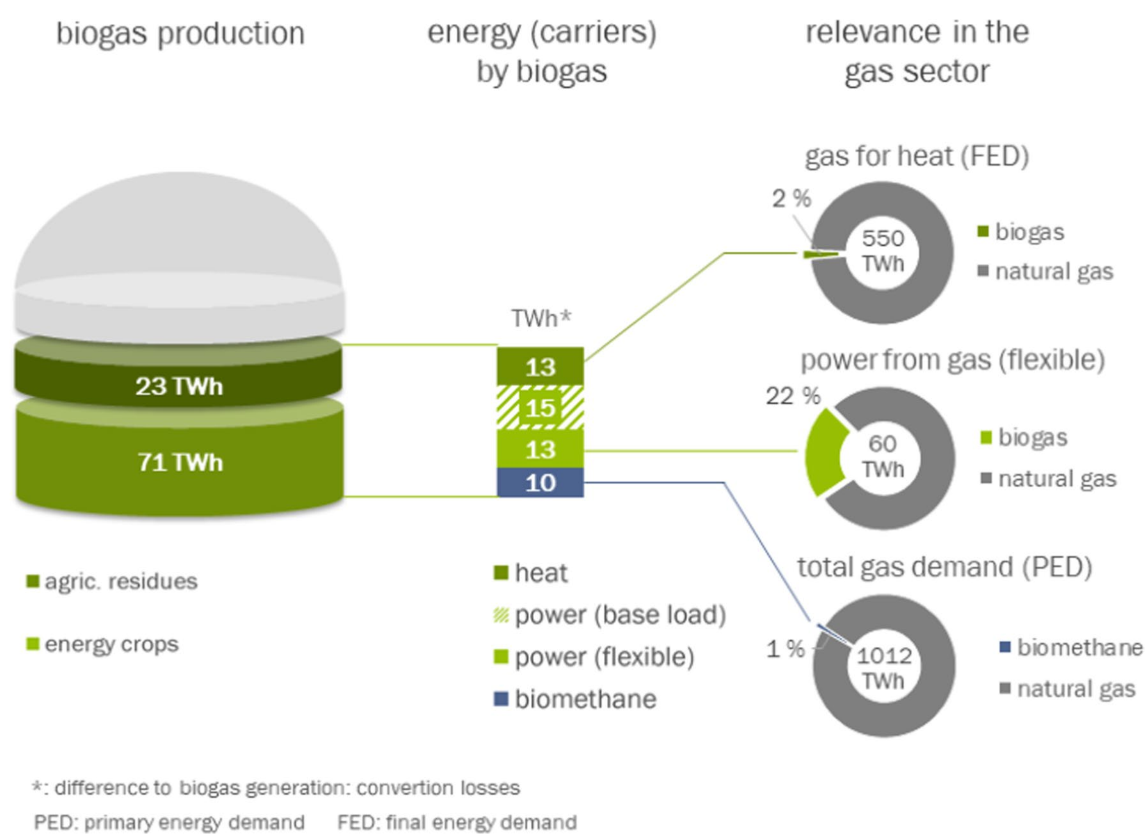

Fig. 4 Current contributions of biogas and biomethane to gas consumption. FED refers to the amount of energy after conversion of biogas or natural gas to heat and/or power. PED refers to the energy content of an energy carrier prior to conversion, meaning that final energy output will be lower due to conversion losses depending on the efficiency of a combustion process in the case of energetic uses

(c) Processing of biogas to biomethane and injection into the gas grid is currently carried out to the extent of approx. 10 TWh/a. This corresponds to about 1% of the current natural gas consumption in Germany. This biomethane is then used for power generation, as a fuel, and to a marginal extent for pure heat supply, and could potentially replace natural gas in other areas of application (e.g., material use in the chemical industry).

Impact of higher agricultural prices on biogas production

In volatile markets and political environments, the role of biogas for energy supply is permanently changing. Since the beginning of the war in Ukraine in February 2022, the production conditions as well as income opportunities have shifted notably. One key development to consider here is the rising price of biogas substrates, which has been affected by the war in multiple ways. Whether the production level of biogas in 2021 can be sustained in the near future will therefore depend on whether prices for key substrates, such as maize and wheat, still enable a competitive use in biogas plants. This question is also interesting as it provides insights for policy-makers whether they have to intervene into energy markets for the sake of food security.

Table 1 shows the results of the calculation of the maximum payable silage maize prices in relation to the REA payments for the German standard biogas plant. The calculation is based on the REA remuneration on the right side of the table. The reference maize prices are derived from the REA payments using a German standard biogas plant. The reference price for silage maize is the maximum price that can be paid by the standard biogas plant at a given REA payment in order to cover costs. The equilibrium prices for wheat and grain maize were derived from this price for silage maize. If this price is reached or exceeded on the free market, silage maize is no longer competitive for biogas use. Also, the gross margin is given in the table. The gross margin in Table 1 is the equilibrium that arises with the given price for maize. From the DBFZ operator survey, it can be deduced that the average REA feed-in tariff paid in Germany is approx. 0.185 €/kWh. According to the calculations, this results in a maximum payable price of 40 €/t silage maize as a biogas substrate,

Table 1 Results of the equilibrium price calculation

	Equilibrium price calculation		Reference price calculation	
	Wheat	**Corn (grain)**	**Silage maize (reference)**	**EEG payment [€/kWh]**
Gross margin [€/ha]	2351.41			0.228
Equilibrium price [€ t/FM]	390.09	332.85	60.00	
Gross margin [€/ha]	2101.41			0.217
Equilibrium price [€ t/FM]	358.41	307.26	55.00	
Gross margin [€/ha]	1851.41			0.206
Equilibrium price [€ t/FM]	326.72	281.67	50.00	
Gross margin [€/ha]	1601.41			0.196
Equilibrium price [€ t/FM]	295.03	256.08	45.00	
Gross margin [€/ha]	1351.41			0.185
Equilibrium price [€ t/FM]	263.35	230.50	40.00	
Gross margin [€/ha]	1101.41			0.174
Equilibrium price [€ t/FM]	231.66	204.91	35.00	
Gross margin [€/ha]	851.41			0.164
Equilibrium price [€ t/FM]	199.98	179.32	30.00	
Gross margin [€/ha]	601.41			0.153
Equilibrium price [€ t/FM]	168.29	153.73	25.00	
Gross margin [€/ha]	351.41			0.142
Equilibrium price [€ t/FM]	136.61	128.14	20.00	
Gross margin [€/ha]	101.41			0.132
Equilibrium price [€ t/FM]	104.92	102.55	15.00	

The calculation is based on the REA remuneration on the right side of the table. The reference maize prices are derived from the REA payments using the German standard biogas plant. The reference price for silo maize is the maximum price that can be paid by the standard biogas plant at a given REA payment in order to cover costs. The equilibrium prices for wheat and grain maize were derived from this price for silage maize. If this price is reached or exceeded on the free market, silage maize is no longer competitive for biogas use

which corresponds to an equilibrium price of 263.35 €/t for wheat and 230.50 €/t for grain maize (Table 1). Figure 5 visualizes the dependency of the marginal prices of wheat and grain maize in relation to the REA feed-in tariffs and the resulting maximum payable maize silage prices for the German standard biogas plant and aggregates the results from Table 1 graphically. In addition, wheat and grain maize prices are included. It can be concluded that in comparison to wheat, maize silage is not competitive at the Matif price levels (Delivery May) for wheat until an REA payment above 0.23 €/kWh is achieved. The results are considered for the German standard biogas plant defined here.

Between 2005 and 2020, average producer prices in Germany ranged between 96 and 220 €/t for winter wheat and 104 and 211 €/t for grain maize [31]. This means that plants were, on average, competitive throughout Germany even in phases of relatively high prices, when comparing the figures which included the average REA feed-in tariff of 0.185 €/kWh assumed for Germany.

With the onset of the Ukraine conflict on the 24 February 2022, the trading prices on the Matif commodity futures exchange (Marché à Terme International de France*)* for wheat and grain maize rose rapidly. Wheat was at times around 420 €/t and grain maize around 370 €/t [32]. In view of these increased prices, the production of silage maize as a biogas substrate is currently not competitive in respect to the gross margin compared to wheat and grain maize for the average agricultural biogas plant in Germany. With a view to the expected trade price development for winter wheat and grain maize, this situation might persist in the next two seasons: a Matif winter wheat price of 407 €/t (delivery May 2022) only covers costs with a power tariff of approx. 0.235 €/kWh. For grain maize with a Matif price of 361 €/t (delivery June 2022), the cost recovery threshold is close to 0.24 €/t. At present, there are signs of a slight easing in prices, but they remain at a high level (Additional file 1: Annex, Table SA2. 4). It is therefore to be expected that silage maize production for biogas will remain economically difficult in the coming years at least for those plants which have fixed remuneration schemes and do not profit from increasing power prices.

Estimated impacts of higher prices as well as price volatility for power from biogas plants

Prospects for biogas production are not only affected by higher prices for agricultural substrates. A second development to consider are the rising prices for energy in Europe, which provide opposite incentives in the direction of an increase of biogas production. Plant operators that run an on-site CHPU or, indirectly, as well as a biomethane CHPU, can gain additional revenues on the power market [33, 34] on top of REA subsidies. This could lead to a higher willingness to pay for input materials. As explained in the previous section, for most biogas plants public subsidies instead of market prices used to be the dominant source of income. However, an increasing number of plants have been modified following the introduction of incentives for flexible power generation since 2012, when a flexible premium was introduced. These incentives include the option to augment subsidy payments with revenues based on the volatility of power

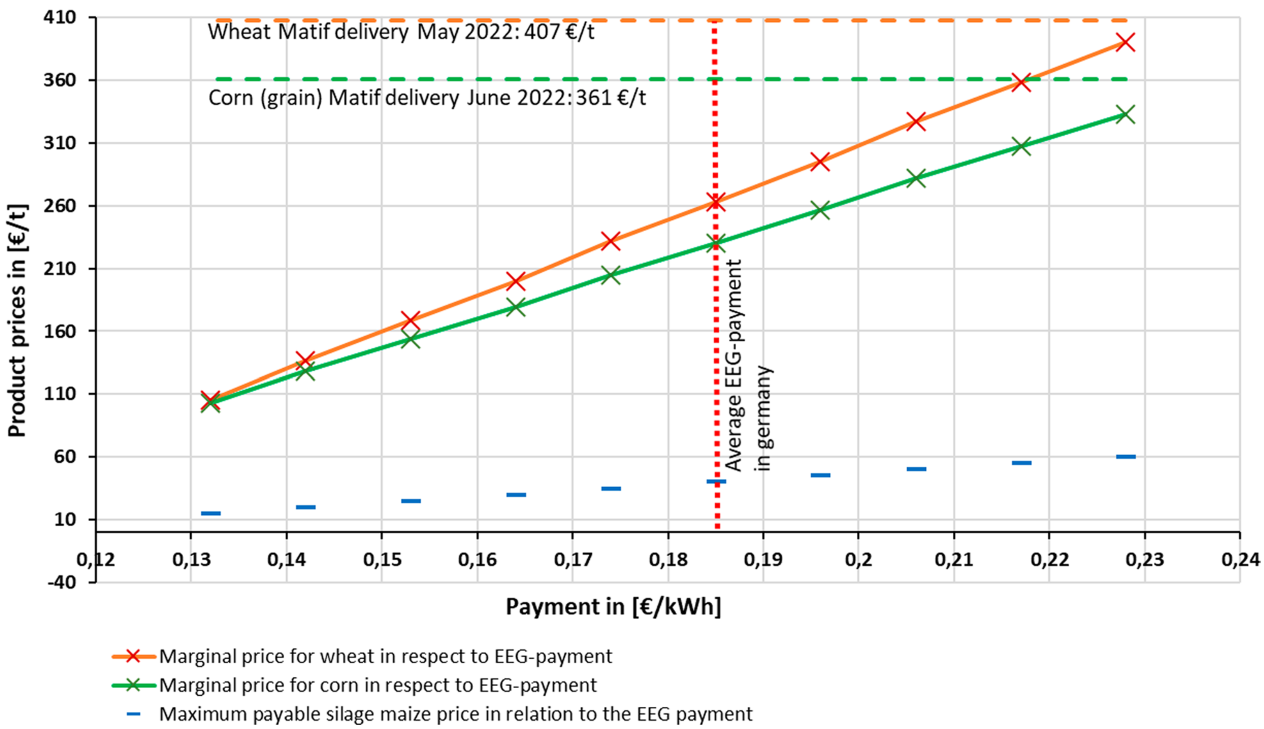

Fig. 5 Competitiveness of silage maize in comparison to the alternative cultivation options of winter wheat and grain maize in relation to their current trade prices and in dependence on REA payments

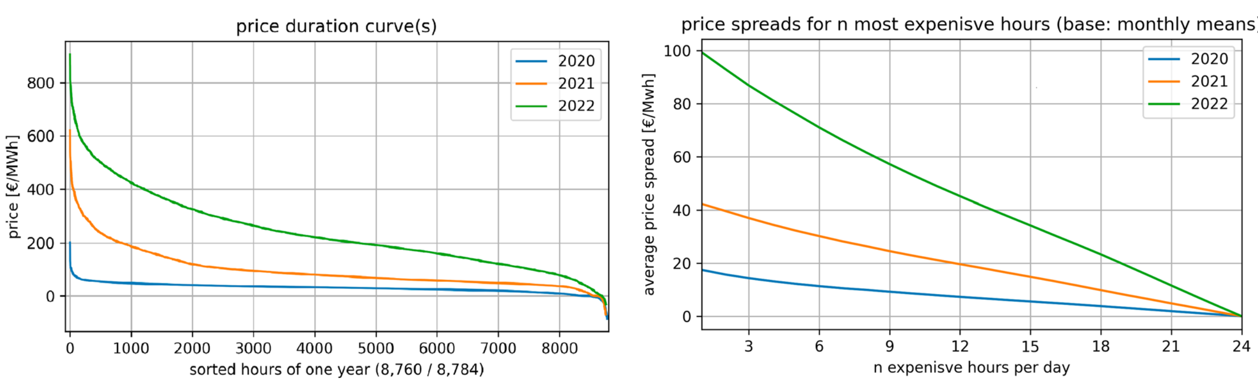

Fig. 6 Price duration curves for EPEX-Spot (left) and average dynamic price spreads for the *n*-best hours per day comparing to daily averages (right), market-zone DE-LU [24]

market prices. We assume, that approximately one-third of Germany's biogas plants, which have already obtained the flexible premium [35], are prepared and capable of reacting malleably to price changes at the power market. Due to the rise of the absolute price level at the German power spot market (see Fig. 6), those CHPU operators can gain extra earnings if the power price exceeds the REA's remuneration level for the individual plant. During the last decades, power prices ranged below remuneration levels more or less constantly, and the REA did explicitly just guarantee positive market premiums. If prices exceed the remuneration level, the difference can be fully exploited as an extra revenue.

Over the last years, power prices have not only increased in absolute numbers, but have also become significantly more volatile. As shown in the right subplot of Fig. 6, dynamic price spreads, for example best 12 h per day, were less than 10 €/MWh in 2020, 20 €/MWh in 2021 and almost 50 €/MWh in 2022.

Due to revenues depending on both power market prices in general and price volatility, incomes differ substantially between individual plant concepts. Nevertheless, the specific revenues for power prices above an assumed feed-in tariff is about 6.57 Ct/kWh (considering EPEX Spot prices until 31st of October). The additional revenues for price-driven power generation for flexible biogas plants can be estimated using a moderate degree of flexibilization with a power quotient (PQ = installed capacity / rated capacity) of PQ = 2, which is equal to a daily runtime of 12 h. According to Fig. 6, in 2022 the gross price spread for the 12 best hours of each day is around 50 €/MWh. If one accepts that biogas plants could not fit perfectly to the ideal generation schedule and an average share of optimal marketing of 80% is assumed, together with an assumed profit-sharing rate of 80% between the direct marketer and the plant operator, 3.2 Ct/kWh can be additionally generated. Thus, the total specific income for the given assumptions will reach 28.3 Ct/kWh.

When the German government agreed to the "Electricity price brake and skimming off of additional revenues law" on the 15th of December 2022, power from biogas got an exemption from skimming off of additional revenues [36]. So, the additional (and also now politically agreed upon revenues) could shift the total willingness to pay for energy crops and other substrates. Market prices for energy and for agricultural commodities show some correlation. Hence, biogas production will not necessarily decrease in case prices for grain/cereals continue to rise.

Summary of results

The analysis of the current role of biogas in Germany indicates that biogas mainly refers to the power (and combined heat) sector. Biomethane, which has the potential to substitute natural gas via the gas grid, is still of minor importance at the moment. Regarding a secure gas supply in Germany, the contribution of biogas is limited by high uncertainties of energy crop availability for biogas production, which might even endanger current production. On the other hand, biogas has the potential to contribute more to power supply security, via a higher degree of flexibility under stronger electricity market signals.

Discussion

Options to sustainably increase biogas provision in Germany

To optimize the contribution of biomass to gas supply, both changes in the production and use of biogas should be considered. However, it must be taken into account that the major share of biogas in Germany is provided from energy crops, which are increasingly being diverted to other markets (animal feed) as a result of rising prices for agricultural raw materials. Thus, before considering the expansion of biogas production, measures must first be taken to secure the current production level. Overall, five key measures to improving gas supply security through biogas are possible:

Measure 1: conversion of the substrate base to ensure biogas production Currently, 13% of the arable land in Germany is used to produce biogas substrates [37]. Cultivated biomass (energy crops) provides the majority (78%) of the energy contained in biogas [25]. Since many biogas substrates used today can also be used as food (dual use), a shift of biogas substrates to the market fruit production can currently be observed with increasing demand for food. Bioenergy can and should have a buffering effect on food markets in this way, contributing to food security. A shift from cultivation of energy crops toward food crops (bakery wheat) is also likely.

Maintaining the contribution of biogas to energy supply security therefore requires a rapid shift to agricultural by-products and biogenic waste. A wide range of sectors still promising untapped potentials for by-products and waste for energy purposes (27—76 TWh/a) can substantially contribute to the substitution of energy crops (currently approx. 70 TWh/a) [16, 38]. Other promising feedstocks are crops that do not require additional land (e.g., catch-crops or biomass from maintenance of nature conservation areas). When the digestate is returned after energy production to arable land, it contributes to humus build-up [40]. However, mobilization and competing material uses might limit the contribution of agricultural by-products and biogenic waste to the energy sector.

Efforts to reform the substrate base for biogas in the direction of substrates which do not compete for arable land should nevertheless not lead to a categorical exclusion of the energetic use of arable crops. This would erase bioenergy's positive effects for food security in terms of stabilizing agricultural prices and thus income for farmers [41].

Measure 2: accelerated flexibilization of power generation from biogas Power generation can be made more flexible, for example by increasing the power generation capacity of biogas plants or by adding gas storages. By and large, the current production of 28 TWh/a of well controllable power could be generated in flexible mode in 2030. This would correspond to up to 46% of the power supply from natural gas. However, the potential decline in biogas production from energy crops as well as economic barriers, especially for smaller plants, must be taken into account.

Further flexibilization of the existing plants is already stimulated by the current regulatory framework supporting the production of biogas. Since 2014, public subsidies for power output under the REA have been complemented by separate payments for excess capacity as a precondition for flexible power generation. Furthermore, since 2017, output-based subsidies have been restricted to a certain share of capacity in order to further incentivize flexible power generation. However, this quasi-flexibility requirement only applies to a certain range of plants (new installations or existing installations extending their remuneration period). Furthermore, the capacity payments alone are often not sufficient to convince plant operators to switch to a new (flexibility-oriented) remuneration scheme, which is reflected in a low participation in the REA tenders [42]. Therefore, existing incentives should be adapted, e.g., by extending the second remuneration period of existing biogas plants from recently ten to twenty years. This enables plant operators to create long-term prospectives for their assets if they expect a profitable operation in the coming decades. Furthermore, the transformation to flexibility could be accelerated by ensuring flexibility-related extra earnings, which reflects the demand for residual load smoothing. The recent regulation of the "Electricity price brake" weakening the price signals for demand-driven operation and could discourage plant operators from investing in flexibility in terms of a new infrastructure as well as in automated generation scheduling.

Measure 3: increasing combined heat and power provision In addition to increased flexibility in power generation, optimizing heat use in the combined heat and power systems can also contribute to the substitution of natural gas. The potential for increasing the use of heat in existing biogas plants has been assessed by Steubing et al. [showing the potential for a slight increase in the biogas-based share of gas-based heat from 2% to about 3% (approx. 16 TWh)] [17]. This development has also already been encouraged by the REA, since plant concepts with heat extraction have cost advantages and thus better chances for bid acceptance in the REA auctions. Important factors for increasing heat provision are also that the biogas operator owns the heat grid and that the contract offers full supply security [42]. In addition, Weinand et al. elaborated that an increasing CO2 price is a powerful instrument to unlock the potential [18]].

Measure 4: expansion of biomethane production In the short term, biomethane supply as a direct natural gas substitute can hardly be increased to any significant extent, since existing plants for upgrading biogas to biomethane usually have a high utilization rate already.

In the medium and long term, an expansion of upgrading capacities as well as the injection of biomethane into nearby gas grids is possible and reasonable. By 2030, an additional 15—20 TWh/a of the current biogas production could be processed in this way [19]. This would increase the possible contribution to gas consumption from 10 TWh/a to approx. 25—30 TWh/a, which would correspond to up to 3% of current German gas consumption. The REA already provides relevant incentives via separate auctions for power from biomethane. It should be noted that biogas plants used for this purpose will no longer be used for on-site power generation. In addition, the diverse applicability of biomethane will increasingly lead to its use for heat and transport as well as for material applications instead of power production. As for the increase in flexible power production, the foreseeable decline in energy crop production must also be considered.

Between the different measures we see synergies and also competition: while a better integration of typically locally available residues and waste streams (measure 1), accelerated flexibilization (measure 2) and excess heat use in CHP plants (measure 3) can be well combined and are applicable in many biogas plants, the expansion of biomethane production (measure 4) is of special interest for larger plants and the competition for substrates.

Beyond these four options—development of additional biomass potentials, accelerated plant flexibilization, use of excess heat and increased upgrading of biogas to biomethane—further contributions of biogas to gas supply security by 2030 are conceivable only through severe restrictions of applicable sustainability requirements and an extensive expansion of government support measures. These steps are, however, disproportionate to the small additional biogas or biomethane volumes that could be generated as a result. In order to reduce dependence on natural gas, other measures, namely reducing consumption, increasing energy efficiency and expanding sector coupling (electrification of heat supply), should therefore take precedence over the former.

Germany's contribution to the REPowerEU Plan

Considering the different limitations and challenges is not only relevant for the German biogas policy but also when discussing Germany's contribution to the REPowerEU Plan, which was one of the EU responses to the Russian aggression [43]. The plan aims to reduce dependency on Russian fossil fuels as quickly as possible by way of energy savings, diversifying energy imports, substituting fossil fuels and accelerating Europe's clean energy transition, smart investments and reinforcing preparedness.

With regard to accelerating the shift to renewable energies, the document explicitly mentions (amongst other measures) the scaling-up of biomethane, with a production goal of 35 billion cubic metres (bn m^3, equals a heating value of 349 TWh, assuming a conversion factor of 9.970 Wh /m^3 biomethane) by 2030. This is nearly double the amount indicated by the Fit for 55 Plan [46] (18 bn m^3, or nearly 180 TWh), and about ten times the current production levels: the entire biogas production of the European Union (EU) amounts to about 18 bn m^3, of which only 3 bn m^3, or 30 TWh, have been upgraded to biomethane [47].

The Staff Working Document [45] that underpins the concrete actions mentioned in the plan in five different areas to achieve this goal. These mainly refer to biogas/biomethane production, grid connection and infrastructures, research and development and access to finance for these measures. The document puts a strong focus on the sustainability of these measures, i.e. possible conflicts with climate; environmental or UN Sustainable Development Goals are given much higher priority here than in other areas of the REPower EU plan (such as increased LNG and coal use). In consequence, wastes and residues are clearly preferred as biogas substrates. As of 2020, over 40% of biogas produced in the EU came from energy crops [47]. This was very much due to Germany's high share of energy crops in biogas production, as the country accounts for over half of the total EU biogas production. Only about 24% (4.3 bn m^3, nearly 43 TWh) were from agricultural residues, including manure [46]. Consequently, any further increase in biogas/biomethane production will need to come almost exclusively from such non-primary resources, no matter in which Member State.

Scarlat et al. [48] deduced the European biogas potential from livestock manure only (i.e. without considering organic and green waste from households, communities or industry, nor residues from agriculture or food/feed processing). They give the total manure volume in the EU at 1,200 M t (at the time of this study, the UK was still part of the EU. Discounting UK figures, this would equal 1,088 M t. All following figures refer to values without the UK share). This puts the theoretical biogas potential at just over 203 TWh. However, as not all manure is collected and real-life anaerobic conversion rates may be lower, they suggest a "realistic" current potential of 145 TWh of biogas, which translates to a "realistic" plant capacity of 47 TWh.

This assumed realistic mobilization rate of 71% is, however, far from that demonstrated in Germany, where calculations by Majer et al. [49] conclude that only about one-third of the technical manure potential is currently being used for biogas production, despite high incentives from the REA.

Moreover, other sources' estimates differ: In Abdalla et al. [44], four of such studies are compared, which put the potential between 300 and over 600 TWh. The noticeably highest figure came from a study including livestock kept outdoors, so the lower end appears to be more realistic. All four sources also include some other type(s) of residual biomass, such as bio-waste, agricultural residues, sewage sludge, or industrial organic waste—but none of them considered all of these. Figures for manure alone are relatively consistent throughout all studies at about 200 TWh. Abdalla et al., however, criticize all of these studies as too optimistic. They are also critical of including catch-crops in biogas potentials. Thus, their own calculations are significantly lower and only add up to 170 TWh (17 bn m^3 biomethane) for 2030, which is not far from the previous ("Fit for 55") EU goal.

Put concisely, all figures assessing the current EU biogas potential have some degree of uncertainty, and assumptions vary widely between the studies. Production increases seem possible, but very much dependent on success in mobilization, and definitely apply to different countries at different levels.

When considering that the current German biomethane production amounts about one-third of the current total EU production (1 bn m^3), it must be emphasized that an additional German contribution to the REPowerEU goals for biomethane is possible but not in proportion to the total increase envisaged by REPowerEU, simply because the German market is already very advanced by comparison to other Member States and under the current uncertainties of substrate availability, the level of biogas production in Germany thus needs to be stabilized rather than increased (at short notice).

Particularly France, but also Italy and the Netherlands have recently overtaken Germany with regard to the number of new biomethane plants built, with Denmark and France leading in the way of production growth rates. Plants in these countries also largely run on agricultural residues—and to a lesser extent on solid municipal or industrial organic waste—instead of energy crops. The above-mentioned substitution effects of food/feed production have therefore much less impact on biogas production in these countries. Moreover, as there were relatively few political incentives for biogas production in Spain or Belgium in past years, there is a substantial untapped potential in these countries [47].

Germany invested substantial resources in biogas production over the last decades, which certainly boosted the sector, and first experiences with the REA's separate tenders for biomethane are equally promising. However, the extensive use of subsidies also has downsides. Next to critics pointing out the high costs and low efficiency of the REA [50], it can be argued that paying subsidies for anaerobic digestion of manure provides incentives for intensive livestock farming, with its well-known negative effects on groundwater and GHG emissions. A more cost-efficient way—avoiding improper incentives—would be to tax emissions from manure or, if this is related to prohibitive transaction costs, make anaerobic digestion mandatory for larger livestock farms.

Limitations of this contribution

When assessing the potential contribution of biogas to a secure gas supply in Germany due to the fact that the 9500 biogas plants in Germany are manifold in biomass supply, biogas utilization and also business models, our reference cases for assessment give some impressions but do not cover all biogas plants.

We also focussed on the biomass availability and the power market conditions as two currently very relevant drivers. Those two aspects became most important after Russia's aggression against Ukraine and the related problems of gas supply security in Germany. In the future, other drivers might present, which are not considered here. Additionally, we also see that potential feedback between biomass prices and power prices is worth further evaluation. The simplified cost-based calculation carried out here does not include these effects. A scenario analysis using representative biogas plant types is of interest here in order to map the costs and yields taking into account the energy market.

This contribution to the debate exclusively looks at biogas production. Additional synergies exist between biogas and solid biofuels as well as with other renewables, but these were not within the scope of this work and need further analysis.

Conclusions and recommendations

The low shares of biogas and biomethane in the gas market as well as the presented challenges for maintaining and expanding the production of biogenic gases show that biomass can only buffer the import dependency for natural gas to a very limited extent. In particular, the availability of sustainable biogas substrates without food or feed competition, but also the increasing use of biomass or biomethane in transport, limit the potential of biogas in substituting natural gas. In order to reduce the dependence on natural gas, other measures should be included, namely reducing consumption, increasing energy efficiency and expanding sector coupling (electrification of heat supply). Nevertheless, given the overall need to switch from fossil to renewable gases, biogas represents an important source for the future renewable gas supply in Germany and the EU. This contribution should be secured and further developed to provide better energy system services, where possible.

Against this background, the following building blocks are recommended for a future biogas policy in Germany. A distinction is made between short-term (within the next two years) and longer-term (more than three years) aspects:

First, an ad hoc programme should be set up to mobilize biogenic by-products and waste, as well as land-neutral cultivated biomass to an amount of 30 TWh/a biogas equivalent. In this way, biogas and biomethane production can be secured to a large extent while quickly reducing the share of energy crops as substrates simultaneously. This can be implemented at short notice, especially through the next revision of the REA via additional incentives for power generation from residues and waste. We would propose a remuneration bonus together with an extension of the remuneration period for successful bids of existing plants, if these plants exceed a certain share of residues and catch-crops, for example, as substrates (e.g., 70 mass %). In addition, we propose to increase the biogas production from manure by extension of the fixed remuneration for manure fermentation, currently limited to plants with a maximum installed capacity of 150 kW. Alternatively, and more efficiently, anaerobic digestion of manure could be incentivized by an emission tax or could be made mandatory.

Second, a more energy system-oriented contribution of the existing biogas plants to the power and heat sector can be unlocked in the short term: the flexibility potential in existing biogas plants must be made more attractive, so that plant operators decide to switch their plants at least in a follow-up compensation period in the REA. This can be stimulated by increasing capacity-related payments as a prerequisite to finance flexibility services. Alternatively, the above-mentioned extension of the payment period for the use of biogenic by-products and waste could provide another important incentive. In addition, the REA's flexibility requirements for extended or new biogas plants can be further tightened step by step and tender volumes can be increased accordingly. Here, higher payments for flexibility can ensure counter-financing, too.

Third, biomethane incentives should be aligned between the power sector, the transport sector and also other sectors in the shorter term, so that the long-term efficient use of biomethane as a fuel is not inhibited. In the longer term, other renewable alternatives to natural gas beyond biogas should be advanced through increased research and development. Gasification of lignocellulosic biomass is another promising option for renewable gases from biomass. This process cannot only yield methane, but also hydrogen-rich gases for a variety of material and energy applications. The development and market launch of relevant technologies, which should also be based primarily on residual materials, could be supported, e.g., within the framework of the energy research programme, but also with an agreement to prioritize lignocellulosic biomass for gaseous fuels, which his currently primarily used in the heat sector.

Fourth, supporting energy from biomass should be focussed more directly on greenhouse gas reduction in the longer term. Subsidies, quotas and other support measures for biogas and biomethane should provide incentives for minimizing greenhouse gas emissions that go beyond existing minimum standards. Specifically, in the context of biogas, current subsidies should be examined for how power from biomass can be more strongly aligned with the extent of avoided emissions in the future, as has already been realized in the biofuel sector through the Greenhouse gas Reduction Quota. In addition to minimizing abatement costs, such an approach ensures that those biomass technologies will prevail in the market that are most likely to remain competitive in the future when emission reductions and renewable energy solutions are primarily incentivised by emission trading systems instead of subsidies mainly focusing on energy output. In this way, future structural breaks can be avoided and investors can be given the necessary security for long-term investments.

Fifth, to support REPowerEU, mobilization of residues is an issue for biogas and biomethane production in all European countries in the short and in the longer term. With the experiences from Germany, we see the need to especially activate agricultural residues from livestock production for biogas, e.g., by making anaerobic digestions of livestock excrements mandatory from certain farm sizes upwards—not only for Germany, but also on a European scale. Beyond this also supporting mobilization of 'land-neutral' cultivated biomass for energy usage should be ensured in the longer term. As those measures would feed into the Common Agricultural Policy (CAP), biogas/biomethane production would in this case need to be explicitly integrated into its programmes.

On a final note, it is clear that synergies exist between biogas and solid biofuels as well as with other renewables, but these were not within the scope of this work and need further analysis.

Abbreviations

A	Annum
TWh	Terawatt hours
REA	Renewable Energy Act
CSS	Carbon capture and storage
PED	Primary energy demand
FED	Final energy demand
FM	Fresh matter
CHP	Combined heat and power
kWh	Kilowatt hours
DBFZ	Deutsches Biomasseforschungszentrum
t	Tonne
Matif	Marché à Terme International de France
ha	Hectare
h	Hour
PQ	Power quotient
MWh	Megawatt hours
CHPU	Combined heat and power unit
Wh	Watt hour
m^3	Cubic metre
RE	Renewable energy
UN	United Nations
CAP	Common agriculture policy
GHG	Greenhouse gasses
Mt	Million ton
LNG	Liquefied natural gas
EC	European Commission
bn	Billion
EU	European Union

Supplementary Information

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Additional file 1. Calculation of the final bioenergy use. Correlation of market prices of agricultural commodities and energy crops for biogas production. Additional tables.

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