Status quo and perspectives of biogas production for energy and material utilization

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Abstract
Biogas is in many respects a serious alternative to other fossil resources and complements other renewable energy sources from wind and sun. Biogas can be produced in many places decentrally. Its energy potential is high, and it is widely used in the EU and all over the world. With more than 16,000 ktoe of oil equivalent in the EU in 2016, it corresponds to approximately 8% of the total primary energy produced by renewable energies in the EU, produced with nearly 17,000 biogas plants. Nevertheless, the production costs of biogas and its products like energy, heat, and fuel are still too high. Kost et al. (2018) show a comparison of electricity generation costs of different renewable energies and their future potentials. While electricity from huge biogas plants offers generation costs from 10 to 15 ct/kWh, electricity from onshore wind and huge solar systems offers generation costs from 4 to 8 ct/kWh. Although substantial progress has been made with regard to substrate use, production techniques and market designs, many more innovations are needed throughout the biogas value chain for it to be competitive in energy markets without high subsidies. As several papers in the special issue on biogas show, there are numerous innovations and product designs with regard to energy and material uses that could maintain or even increase the importance of biogas production both within and outside of the EU. There are many potential benefits of biogas, as it offers high shares of produced renewable energies as well as large amounts of material products like digestates and in future maybe products of higher value such as proteins or lactic acids.

KEYWORDS
biogas, biomethane, food waste, material use, methanation, miscanthus, perennial crops, power-to-gas, repowering measures

1 | INTRODUCTION

Biogas is a multifunctional, renewable secondary energy source produced by anaerobic microbial conversion of biomass from different sources. Biogas provided more than 16,000 ktoe of oil equivalent in the EU in 2016 (see Figure 1). This corresponds to approximately 8% of the total primary energy produced by renewable energies in the EU and is produced in approximately 17,000 biogas plants (EBA, 2018; Kampman et al., 2016).

This amount of biogas production was only possible with the support of substantial subsidies granted in some European countries. This resulted in an average growth rate of 17% per annum (p.a.) in biogas capacity in the EU in the period 2005–2015. However, this has decreased to a currently marginal growth rate of about (expected) 1% p.a.
Over the past 15 years, in addition to the previously established plants producing biogas from bio-waste, on-farm biogas production based on energy crops became prominent. With regard to the primary energy produced, the latter also builds the focus of biogas production in many EU member states, for example, in Germany, a country which produces 50% of primary energy provided through biogas in the EU (see “Others biogas from anaerobic fermentation” in Figure 1). This amount of energy production was enabled by subsidies, often granted as guaranteed feed-in tariffs for electricity produced from biogas. The prevailing substrate used depends on the individual countries’ subsidy regulations for the production of secondary energy from biogas. Often the substrates occur from cultivated energy crops (in particular silage maize) as well as farm manure and slurry (Achinas, Achinas, & Euvering, 2017). The latter is used for biogas production in Germany, Italy, Czech Republic, Austria, Slovakia, Denmark, or Slovakia (Bartoli, Cavicchioli, Kremmydas, Rozakis, & Olper, 2016) (see Figure 1). In many other countries like Estonia, Finland, Portugal, or Romania (see Figure 2), alternative biomasses, which originate from waste processes such as sewage sludge or food residues, form the focus of biogas production. Those production plants have sometimes already existed for many decades (Kampman et al., 2016). Although there is no detailed knowledge of the various biogas substrates used in individual EU countries, CE Delft, (2016) estimates their share for 2014 using various EU and national statistics as shown in Figure 2.

Biogas can be produced from small (2 kW) to large (20 MW) plant scales and be used in multiple ways, especially for electricity and heat generation in combined heat and power plants (CHP) directly installed at the production site. Germany’s strong focus on this kind of its biogas usage results in approximately 4% of gross electricity production currently being provided by biogas production (Lauer & Thrän, 2017, see also Figure 3). Germany has another special feature in comparison with other countries. There is an increasing “overbuilding” of the plants, which can be connected with a considerable capacity increase but without producing more electricity and heat per biogas plant per year (Güsewell, Härdtlein, & Eltrop, 2019). The CHP output can, for example, be doubled in this “overbuilding” measure in order to produce the same amount of energy in half the annual operating time. In particular in Germany, this has become a common production model in order to take advantage of the production flexibility for biogas and electricity, which can be adapted to the actual electricity demand. Electricity prices increase with electricity demand. Solar and wind power cannot take advantage of these higher prices at peak demand because the required storage technologies are still too expensive. In particular in Germany, such capacity increases are being subsidized, so
that an interesting business model can result for the biogas plant operators.

National subsidy models for investments in biogas plants and for energy sales prices vary among European countries. The subsidized electricity prices or feed-in tariffs can be fixed or minimum prices, some of which are market-oriented and increased by subsidy surcharges and are limited in some cases by quotas (Kost, Shammugam, Jülch, Nguyen, & Schlegl, 2018). Heat is partly used by the producers themselves (e.g., for heating the fermenters, their own buildings, or used in other branches of their own business such as aquaculture), and some is sold to third parties (Herbes, Halbherr, & Braun, 2018). Heat sales are usually more geared toward general market developments than electricity sales (Hakawati, Smyth, McCullough, Rosa, & Rooney, 2017). In addition to the biogas plants outlined above, which mainly produce electricity and heat on site, in recent years, more and more plants have been built to upgrade biogas into biomethane. This approach enables a temporal and spatial decoupling of the biogas production from its utilization. After injecting the biomethane into the natural gas grid, it can be used elsewhere for electricity and/or heat production or for fuel production. The number of biomethane feeding plants in Europe amounted to approx. Four hundred plants with a production and processing capacity of 300,000 to 400,000 m³/hr of raw biogas (see EBA, 2018) most of them are installed in Sweden (see Figure 3). The feeding in of biomethane creates spatial and temporal flexibility for energy use, which can provide a higher added value compared to other renewable energies such as solar and wind (but also compared to raw biogas), at least as long as storage technologies for solar and wind power are still cost-prohibitive.

In developing countries, biogas production offers an ideal opportunity to use it directly in a burner or to self-produce electricity and heat and use it in addition to solar energy. The advantage is that no expensive grid infrastructure is required, which is anyway often lacking in these regions. Scarlat, Dallemand, and Fahl (2018) give an overview of biogas production in developing but also in developed countries. Biogas can also be processed into fuel for vehicles, something mostly done in developed countries (Khan et al., 2017). This has the advantage, among others, of being able to reduce the previously high nitrogen oxide and fine dust emissions, but also the climate impact compared with combustion of fossil fuels (e.g., Scarlat et al., 2018; Cong, Caro, & Thomsen, 2017; Patrizio, Leduc, Chinese, Dotzauer, & Kraxner, 2015; Patrizio, Leduc, Chinese, & Kraxner, 2017). Finally, material uses of biogas processing products besides the energy use of biogas itself are also conceivable, ranging from fertilizer use of fermentation residues to the production of pure substances for industrial processes. Against this background, the biogas value chain is examined in this Special Issue (SI) in chronological order (see Figure 4), which begins with production and processing of substrate for biogas production.
Subsequently, the technical process of biogas production will be taken up, in which hydrogen methanation forms an important focus and which could be of great importance as a power grid stabilization service in the future. Finally, the use of biogas for energy and material processes is described. This also involves technical and economic efficiency analyses to enable the “biogas” value chain to be more competitive compared with other fossil and renewable energies. Thus, the objective of this contribution is to identify and discuss the potential for technical, economic, and ecological improvements of the value chains in the biogas system.

2 | SUBSTRATES

A large part of the latest research on biogas substrates deals with renewable raw materials of agricultural origin. While in the past, the focus was on annual plants, perennial plants and waste materials are currently becoming more important. Table 1 classifies the most important substrates into different categories.

So far, maize has been the preferred agricultural substrate for biogas production. Maize has high dry matter yields, good silage and storage properties, and good fermentation properties with related high methane yields per hectare at relatively low biomass supply costs (Auburger, Jacobs, Mürländer, & Bahrs, 2016). However, the strong expansion of silage maize cultivation of nearly one million hectares in Germany because of biogas production (FNR, 2018) is also associated with considerable, in some cases undesirable ecological effects, which maize growers and biogas producers do not sufficiently consider from an economic point of view. It can lead to a number of negative environmental impacts, such as loss of biodiversity (Otte, 2010), soil erosion, and nitrate leaching, if good agricultural practices are not adhered to (Svoboda et al., 2013). In addition, the low aesthetic value of maize has led to the deterioration of biogas production's image in public perception. Other substrates can be ecologically better at this point. Depending on the region and type of production, these may include grasses, the mixed silphy, but also...
miscanthus (Auburger, Petig, & Bahrs, 2017; Popp et al., 2017). Such perennial crops have the advantage over annual crops, such as maize, of requiring fewer resources and increasing the positive or decreasing the negative environmental impact per product unit (Kiesel, Wagner, & Lewandowski, 2017). Perennial crops reduce the risk of erosion, lead to soil carbon accumulation, and improve soil fertility. They reduce the risks of biomass production because they deliver more stable yields over the years than annual crops, which are more influenced in their establishment and growth by precipitation and temperature conditions (Ehmann, Bach, Laopeamthong, Bilbao, & Lewandowski, 2017; Lewandowski, 2016). Both Wagner et al., (2019) and Mangold, Lewandowski, & Kiesel (2019a) take up this point of positive ecological effects of alternative substrates in their contributions and exemplify it with miscanthus. Although miscanthus has so far mainly been used for heat production and material applications, targeted use in biogas plants can also be important in the context of taking ecological effects into account, especially as the methane hectare yields of miscanthus can keep up with those of silage maize (Kiesel & Lewandowski, 2017). As with many other substrates, it is important to choose the right genotypes and the right harvest time for biogas production from miscanthus. Genotypes with higher leaf proportion are promising, as leaves show a higher substrate-specific methane yield than stems (Mangold, Lewandowski, & Kiesel, 2019b). As demonstrated by Mangold et al., (2019b), a harvest in mid-October resulted in the highest dry matter and methane hectare yields and additionally maximized nutrient recycling compared to a harvest in mid-September. Also, a harvest in mid-October resulted in best silage quality (Mangold et al., 2019a). Therefore, mid-October is likely to be the most suitable harvest date for a green-cut of miscanthus in Germany. Storing is a relevant issue for anaerobic digestion, as a continuous feeding is necessary in most biogas plants. So far, ensiling is the best-known preservation technique for biomass. (Mangold et al., 2019a) demonstrated the ensiling ability of miscanthus biomass and showed positive effects of ensiled miscanthus on digestion-velocity compared to nonensiled miscanthus. Mass losses of up to 7.6% of fresh matter for the Miscanthus sinensis genotype Sin55 were compensated by a higher substrate-specific methane yield (up to 353 ml CH₄ (g oDM)⁻¹), which resulted in a methane hectare yield of 4757 m³ CH₄ ha⁻¹ for ensiled miscanthus (Mangold et al., 2019a). To enable a large-scale use of perennial crops such as miscanthus, implementation barriers must

**FIGURE 4** Value chain of biogas (PLA, polylactide; VFA, volatile fatty acid)

**TABLE 1** Categories of substrates for biogas production and exemplary important substrates

| Annual crops | Perennial crops | Biowaste | Others |
|--------------|----------------|----------|--------|
| Maize silage | Grass          | Food residues | Algae  |
| Whole plants | Mixed silph    | Animal manure and slurry |        |
| Sugar beet   | Miscanthus*    | Municipal solid waste |        |
| Grain        |                | Sewage sludge     |        |

*Assessed in this issue.
first be removed for farmers who are afraid of a 20-year fixation of the land to one crop with above-average initial investments. Wagner et al., (2019) demonstrated that using miscanthus as a biogas substrate has the potential to decrease the costs of biogas generation considerably in comparison with maize. In addition, the substitution of a fossil reference through electricity generated by the combustion of miscanthus-based biogas leads to substantial net benefits in the impact categories climate change, human toxicity, marine and freshwater ecotoxicity, and freshwater eutrophication. The substitution of 1 GJ of the marginal German electricity mix for instance, which was used as the fossil reference, results in a carbon mitigation potential of 934 kg CO2eq. (Wagner et al., 2019). In addition, Kiesel et al. (2017) compared the environmental performance of biogas produced using maize and miscanthus as substrate. They showed that the miscanthus-based biogas production has significantly lower impacts on the environment in comparison with maize. However, despite these advantages of miscanthus, silage maize, sugar beets, and whole crop silage are still the dominant biogas substrates. Adequate remuneration for positive external effects or reduced negative external effects could help to establish miscanthus as a biogas substrate. Similar conditions also apply to other substrates not yet outlined, but often mentioned in the scientific literature. For example, algae are also being considered as substrate (see Milledge & Heaven, 2017). The more area-independent production of this biomass initially appears to be excellent compared with area-intensive substrates such as maize, sugar beet, whole plant silage, or even perennial crops. Further, it would not compete with food production. However, methane production costs are comparatively high and the positive ecological effects compared to other substrates are not yet high enough to justify extensive practical use (Montingelli, Tedesco, & Olabi, 2015). To minimize competition with food production, other substrates are of greater relevance (Britz & Delzeit, 2013). Organic waste, especially food residues but also grassland biomass, especially combined with manure as cosubstrate, offers comparatively high methane yields (Lalande, Nordberg, & Vinneras, 2018) and good ecological properties with low competitive potential for food production (Hamelin, Naroznova, & Wenzel, 2014). Furthermore, the volume potential of these substrates is estimated to be considerable in the EU 28. Animal manure, straw, and grass potentials on its own show already considerable potentials. “The biogas energy potential from all the mentioned biomass was projected to range from 1.2*103 to 2.3*103 PJ y⁻¹ in year 2030 in the EU28, depending on the biomass availability. Even on its own, the biogas energy potential projected in the scenario representing low substrate availability corresponds to a doubling of the European biogas production in 2015” (Meyer, Ehimen, & Holm-Nielsen, 2018). Individual authors have analyzed which fermentable substrates could be used in large conurbations, while at the same time providing adequate acquisition options. For example, DeClercq, Wen, Fan, and Caicedo (2016) estimate Beijing’s volume of potentially usable food residues at 956,300 tons per year, with a resulting volume of 300 million Nm³ of methane (DeClercq et al., 2016). Woon, Lo, Chiu, and Yan (2016) estimated that turning Hong Kong’s 1,080 tons per day of food waste into biogas vehicle fuel as petrol substitute would reduce 1.9% of greenhouse gas emissions in its transport sectors, which would result in a larger decrease in GHG emissions than the reduction achieved in Hong Kong from 2005 to 2010 (see also Shen, Linville, Urgun-Demirtas, Mintz, & Snyder, 2015). If suitable collection and separation systems for food waste in households were in place and technical improvements of the biogas process were implemented, the environmental impact could significantly improve (Eriksson, Bisaillon, Haraldsson, & Sundberg, 2016). Nevertheless, more technical innovations are necessary to overcome the obstacles of high costs or low revenues in biogas production (inter alia from waste). Subsequently, this innovation potential will be taken up and discussed in the overall context of energy production.

3 | TECHNICAL FRAMEWORK CONDITIONS FOR BIOGAS PRODUCTION IN THE CONTEXT OF ANAEROBIC DIGESTION

The type of substrates used has led to considerable progress in efficiency and effectiveness in biogas production. Their combinations, which have changed over time, have contributed to a considerably higher process stability. Finally, the advanced technologies for obtaining biogas in and around the fermenter have also made considerable progress (Angelidakis et al., 2018). However, these advances are not enough to make biogas production able to compete on a large scale with other renewable energies in the future. This will be discussed later in the context of Güsewell et al., (2019). Further technological progress is therefore also needed in the field of fermentation and its process in order to achieve higher competitiveness (Achinas et al., 2017). Biogas is a product of microbial degradation of organic substances in a humid environment under airtight conditions (anaerobic environment). The fermentation process basically takes place in four interdependent substeps (hydrolysis, acidogenesis, acetogenesis, and methanogenesis), in each of which different groups of microorganisms are involved (Weiland, 2010). In commonly used one-stage biogas systems, the four phases take place simultaneously in the same fermenter. Because the different microorganisms have their specific demands, the
CO₂, H₂ can be converted into methane (CH₄) (methane-renewable electricity (especially from wind or sun). Using hydrogen (H₂) and oxygen in electrolyzers using excess plants. In power energy system services are further expanded by biogas (2017).

With the power-to-gas technology, the possibilities of energy system services are further expanded by biogas plants. In power-to-gas systems, water is first split into hydrogen (H₂) and oxygen in electrolyzers using excess renewable electricity (especially from wind or sun). Using CO₂, H₂ can be converted into methane (CH₄) (methanation). It can easily be fed into the existing natural gas networks. Classical, chemical–physical methanation processes are comparatively expensive because they require high pressures, high temperature, and pure source-gases. In biological methanation, hydrogen and carbon dioxide are converted to CH₄ and water by methanogenic microorganisms.

Biological hydrogen methanation (BHM) is currently the subject of many research projects and publications, especially in combination with biogas plants (Burkhardt & Busch, 2013; Lecker, Illi, Lemmer, & Oechsner, 2017; Ullrich et al., 2018). The CO₂ fraction of biogas serves as a C source for CH₄ formation. The aim of the current investigations was to increase the reactor-specific CH₄ formation rates (MFR: Methane Formation Rate), which is currently still significantly lower than in the chemical-catalytic processes (Lecker et al., 2017). In principle, biological hydrogen methanation can take place simultaneously with biogas production in the same fermenter (in situ methanation). Hydrogen is injected directly into the biogas fermenters via membranes, sinter stones, or aeration agitators. It is converted to methane by hydrogenotrophic methanogenic microorganisms in combination with CO₂. This significantly increases the H₂ content of biogas. Alternatively, the conversion of CO₂ and H₂ can also take place in external bioreactors that are connected downstream of a biogas plant (ex situ methanation). These external reactors are often designed as bubble column or trickles bed reactors. A promising concept is the biological hydrogen methanation in high-pressure trickles bed reactors by combining very large phase contact surfaces with an accelerated phase transition due to high partial pressures. Ulrich and Lemmer (2019) describe a technically promising method for future biological methanation.

After dehumidification, pressure adjustment, and odorization, the methane obtained at BHM can be used for mobility purposes or fed into natural gas networks. The fermentative high-pressure conversion of H₂ to CH₄ is thus a solution approach for a sustainable energy supply in rural areas. At the same time, the process links different energy generation and transport systems and therefore represents an efficient storage and transport option for energy. The special feature of this process is the conversion of electrical energy into chemical energy and the production of methane independent of biomass as a substrate when alternative CO₂ sources are used. The vector technology of power-to-gas (PtG) processes for linking electricity and natural gas networks is therefore also regarded as a key technology for storing renewable energies.

4 | MATERIAL USE OF BIOGAS PRODUCTS

There are also options for material uses of products generated in the biogas process, including digestates, which are used in particular as fertilizers in agricultural production (Ehmann, Thumm, & Lewandowski, 2018). Numerous authors are dealing with the optimal utilization of digestates as a source of nutrients, as they contain the important nutrients nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca). This attributes them with high saving potentials compared with mineral fertilizers (up to 25 € t⁻¹, Rolink, 2013). Many authors confirm the high nutrient value of fermentation residues, also in comparison with mineral fertilizers (Barbosa, Bogdanov, Vainikka, & Breyer, 2017; Formowitz & Fritz, 2010; Gunnarsson, Bengtsson, & Caspersen, 2010; Walsh, Jones, Edwards-Jones, & Williams, 2012). The remaining carbon bound in the organic matter also supports the maintenance or even increase in soil organic matter (Möller, 2015). In particular, marginal yield locations can benefit from this (Nabel, Barbosa, Horsch, & Jablonowski, 2014). Many other questions concerning fermentation residues are dealing with the possibility of humus formation or humus degradation through the use of fermentation residues as fertilizer, with the content of undesirable heavy metals or organic pollutants (Dragicevic, Eich-Greatorex, Sogn,
Horn, & Krogstad, 2018), but also with fractionation into individual nutrients, which is of particular importance for regions with above-average amounts of nutrients (also from regional animal husbandry) and related nutrient exports (Bachmann, Uptmoor, & Eichler-Löbermann, 2016). Furthermore, optimal application techniques are of importance due to the increasing necessity of avoiding ammonia losses (BMEL, 2017). The separation of nutrient fractions from the digestate plays an important role, especially in excess nutrient regions, in reducing transport costs for the export of nutrients. At the same time, the availability of the separated nutrients should also be optimized (also Ehmann et al., 2018; Kahiluoto, Kuisma, ketoja, Salo, & Heikkinen, 2015; Bilbao et al., 2017; Maurer & Müller, 2012; Rehl & Müller, 2011).

In addition to digestate usage, there are other options for material use of individual derivatives from biogas production (Hagman, Blumenthal, Eklund, & Svensson, 2018). The products resulting from the fermentation steps of hydrolysis, acidogenesis, acetogenesis, and methanogenesis can equally be used as platform chemicals for other manufacturing processes. These include, for example, proteins that can be extracted for use in other areas of food production (see Santamaria-Fernandez, Molinuex-Salles, Läbeck, & Uellendahl, 2017). Furthermore, various acids such as lactic acids can be decoupled, which can be used for biopolymer production (e.g., Haag et al., 2016). However, various fatty acids also offer potential for platform chemicals. These also include volatile fatty acids (VFA), which can be used for the production of biodegradable plastics (see also Lee, May Chua, Yeoh, & Ngoh, 2014).

With the support of two-stage processes in which acid formation (hydrolysis and acidogenesis) is spatially separated from methane formation, the quantity and quality of acid formation can be controlled very precisely (e.g., Ravi, Lindner, Oechsner, & Lemmer, 2018). The processes evaluated so far on a laboratory scale offer new and interesting options for the simultaneous production of basic chemicals and the energy source biogas. However, the technical extraction of the VFA is difficult (López, Arnaiz, Merchán, Lebrero, & Muñoz, 2018). Tampio, Ervasti, Winquist, and Rasi (2019) also take up this option in the context of substrate use with biowaste and cattle manure. Biowaste as a substrate shows higher methane yields than other substrates due to its characteristics (pH, organic composition, microbial communities). It is also clear from their contribution that, on the one hand, technical extraction is challenging. On the other hand, it is also indicated that an economic convincing kind of production of VFA is currently still far from market maturity and, therefore, further research is necessary to increase efficiency in order to enrich the biogas value chain with this kind of product extraction.

5 | OPTIMIZATION OF BIOGAS CONCEPTS AND PRODUCTION PERSPECTIVES

Although the production of platform chemicals may be an option for the future, biogas production and its utilization currently concentrates primarily on energy production on the one hand and, on the other hand, on the utilization of fermentation substrates as fertilizer in agricultural use. The technology as well as the type and scope of these products must be optimally adapted to the increasingly competitive markets. Up to now, biogas production in Europe has been strongly influenced by substantial subsidies. In the past, state-guaranteed high electricity feed-in tariffs played a particularly important role. However, this meant that energy production was not geared to the market. As a result, individual European countries changed their funding schemes and geared them toward greater marketability. This includes, in particular, producing electricity when it is needed. “A combination of a daily and seasonal shift in electricity generation might improve the potentials of biogas plants; both PV generation at noon and wind generation in autumn and winter could be better integrated into the electricity system.” (Lauer & Thirain, 2017). However, in many countries, subsidies have been significantly reduced in scope, so that after the expiration of the guaranteed subsidy periods (which in Germany amount to up to 20 years), there is uncertainty as to how things can continue if the cost of energy produced from biogas has to be borne much more strongly by market prices and less by subsidies. Güsewell, Hardtlein, & Eltrop (2019) address this question with their article “A model-based approach to assess effects of repowering measures on existing biogas plants: the case of Baden-Wuerttemberg” and illustrate it using the example of existing biogas plants in Baden-Wuerttemberg, Germany. Various forms of repowering techniques are analyzed. This means that existing biogas plants can be modified by replacing individual parts (e.g., more efficient combined heat and power plants), be adapted to new legal regulations (e.g., expansion of fermentation residue storage facilities), be optimized by modifying process conditions (e.g., improved feed management), or be modified by revising the entire plant concept (e.g., from the conversion of biogas into electricity on-site to the supply of biomethane into the grid). As a result, when applying these potential repowering measures, it becomes clear that even a stronger focus on the electricity market (with regard to its flexibility) than on heat or fuel markets does not guarantee the profitable continued operation of the biogas plants after the current subsidy periods have expired. On the contrary, it becomes clear that, despite many repowering measures geared to the market, a large number of inefficient biogas plants with low earning power in
Baden-Wuerttemberg are still threatened by insolvency. However, in particular, both ecologically and economically above-average biogas producers with high competitiveness will be able to survive on the market with their products—electricity, heat, fuels and fermentation residues. This applies even more if improved technical solutions allow for a more efficient and thus cheaper production of biogas (with regard to substrates and production techniques), especially in comparison with other renewable energies from wind and sun. Future generation plants with higher efficiencies, higher heat yields than before, improved processes of anaerobic fermentation but also lower silo storage losses give reason to hope that biogas will continue to make a substantial contribution to the production of renewable energies in the future. Based on optimistic assumptions, it can be expected that 60%–70% of presently operating biogas plants and the resulting electricity volumes will be maintained until 2035. The remaining plants will grow, and their efficiency will increase. This is another reason why the area of renewable raw materials required for biogas production would be considerably reduced. However, the extent of manure fermentation sought for reasons of climate efficiency would decrease due to its transport cost sensitivity. The model application of Güsewell, Härdtlein, & Eltrop, (2019) and their results have the potential to be transferred to other regions of Germany and Europe, although the specific national funding conditions must be explicitly taken into account in the international context. This means that the future of biogas production could be very strongly linked to the flexibilization of power generation, in which the CHP units produce electricity when it is needed and, thus, can represent a synergy to other renewable sources of electricity from sun and wind, which can be complemented by biogas. Many studies deal with precisely this question and conclude that a minimum amount of electricity from biogas would be desirable in the future energy mix (Lauer & Thrän, 2017). This also requires suitable funding schemes, which especially promote the flexibility of electricity production. However, the future form of subsidies in individual countries is still open and depends to a large extent on how good and how important the system integration of biogas production with the associated electricity production into the renewable energy mix of the future will be.

6 | CONCLUDING REMARKS AND OUTLOOK

Biogas is in many respects a serious alternative to other fossil resources and complementary to other renewable energy sources from wind and sun. Biogas is also renewable and can be produced in many places decentrally. The use of biowaste for biogas production can reduce competition with food markets as the cultivation of substrates on fertile arable soils could be reduced. Böhme (2018) shows that, for example, between 17% and 35% of kitchen waste in Baden-Wuerttemberg ends up in the residual waste bin. The German Biogas Association (FvB) (2015), for example, estimates the amount of biowaste for biogas in Germany on its own between 5 and 6 million t a−1. The global potential should be huge. Biogas is also an energetic all-rounder for electricity, heat, and fuels and can also be the basis for material uses. In all areas of the biogas value chain, there is further potential, for example, considerable potential in efficiency increases. Alternative substrates such as miscanthus have the potential to make biogas production even more ecologically beneficial without increasing production costs compared to other substrates (Mangold et al., 2019; Wagner et al., 2019). Nevertheless, with regard to miscanthus for biogas production, many attributes still have to be analyzed like their role in crop rotations on farms or their environmental and fermentation characteristics.

The production technology of biomethane still shows considerable potential for efficiency improvements in the type of production process, as the contribution of Ullrich and Lemmer (2019) indicates. Changed value chains for biogas, in which material uses, for example, in the form of decoupleable and industrially usable acids, are still in the very early stages. However, Tampio et al., (2019) point out possibilities for future use. Still, biogas and the resulting end products have a major handicap: The production costs are still comparatively high despite a wide range of progress, as shown by the statements of Güsewell, Härdtlein, & Eltrop, (2019), while, for example, the electricity generation costs from wind and sun have been considerably reduced in recent years (IRENA, 2018). “The example of Germany shows clearly that biogas market dynamism is directly linked to the support schemes and the feed-in tariffs implemented.” (Torrijos, 2016). It will also be important how technologies and associated costs of storage technologies develop that are capable of distributing excess solar and wind energy favorably over time and space (Gils, Scholz, Pregger, Tena, & Heide, 2017). So far, there are promising storage concepts that can induce an even higher competitiveness of solar, wind, and water energy compared to biogas (Parra, Norman, Walker, & Gillott, 2017; Barbosa et al., 2017). However, practice concepts that are profitably used on a broad basis can only be expected in the medium term of 10 to 20 years. At least until then, biogas will be an important component of the energy mix in many EU member states and further intensive research for biogas production remains fundamental, both in terms of research on ideal substrates and research on improved production and utilization concepts.
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