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Review

The Future Agricultural Biogas Plant in Germany: A Vision

Susanne Theuerl [1,*], Christiane Herrmann [1], Monika Heiermann [1], Philipp Grundmann [1,2], Niels Landwehr [1], Ulrich Kreidenweis [1] and Annette Prochnow [1,2]

[1] Leibniz Institute for Agricultural Engineering and Bioeconomy, Max-Eyth-Allee 100, 14469 Potsdam, Germany; cherrmann@atb-potsdam.de (C.H.); mheiermann@atb-potsdam.de (M.H.); pgrundmann@atb-potsdam.de (P.G.); nlandwehr@atb-potsdam.de (N.L.); ukreidenweis@atb-potsdam.de (U.K.); aprochnow@atb-potsdam.de (A.P.)

[2] Humboldt Universität zu Berlin, Albrecht Daniel Thaer Institute for Agricultural and Horticultural Sciences, Invalidenstr. 42, 10115 Berlin, Germany

* Correspondence: susanne.theuerl@googlemail.com or stheuerl@atb-potsdam.de; Tel.: +49-331-5699-900

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Abstract: After nearly two decades of subsidized and energy crop-oriented development, agricultural biogas production in Germany is standing at a crossroads. Fundamental challenges need to be met. In this article we sketch a vision of a future agricultural biogas plant that is an integral part of the circular bioeconomy and works mainly on the base of residues. It is flexible with regard to feedstocks, digester operation, microbial communities and biogas output. It is modular in design and its operation is knowledge-based, information-driven and largely automated. It will be competitive with fossil energies and other renewable energies, profitable for farmers and plant operators and favorable for the national economy. In this paper we discuss the required contribution of research to achieve these aims.

Keywords: bioeconomy; biogas; anaerobic digestion; biomass; residues; microbiology; engineering; modelling; technology assessment

1. The Controversial Development of Agricultural Biogas Production in Germany in the Last Two Decades

Biogas production has become common practice or is considered to be implemented or expanded in many countries [1]. This trend can be attributed to a number of advantages combined in anaerobic digestion: it is suitable for manifold feedstocks including diverse types of organic residues; it can be integrated into multi-faceted production systems for food, feed, bioenergy and biomaterials; and it can be adapted in a variety of scales from household to large commercial plants [2–7]. Several countries have promoted biogas production by subsidies either in the form of feed-in tariffs or through supporting investments [1,8–10].

In Germany, the Renewable Energies Act first came into force in 2000 and obliged energy supply companies to feed electricity generated from renewable sources into the grid at guaranteed tariffs over a period of 20 years [1,11,12]. The amendments of the Renewable Energies Act in 2004 and 2009 set strong incentives for the cultivation of energy crops dedicated to anaerobic digestion [13]. In the years 2000 to 2012, the number of biogas plants boosted from 1050 to 8292 [14]. German biogas production now contributes about 50% of the production in the EU [15]. During the same period, the silage maize cultivation area grew from 1,154,500 ha to 2,038,000 ha [16,17]. Electricity prices rose from 13.94 Eurocent per kWh to 25.89 Eurocent per kWh and the included Renewable Energy Act apportionment from 0.20 Eurocent per kWh to 3.59 Eurocent per kWh [18].

While it is not fully quantified to which extent these latter developments are to be attributed to the increase in biogas production, unforeseen side effects of the Renewable Energies Act became obvious and led to strong debates in science and society. Biogas production was discussed in light of the food versus fuel debate by occupying land for energy crop cultivation (e.g., [19]), to biodiversity loss by converting species-rich grasslands into less diverse arable land (e.g., [20–22]), to the increase of land rental prices (e.g., [23]) and to the increase in energy costs by prescribing feed-in tariffs above the prices for electricity from fossil resources (e.g., [13]). Furthermore, the effectiveness and efficiency of subsidizing biogas production was questioned, since with an estimated technical potential of 40 TWh_{el} [12] the contribution of biogas to total gross electricity production (654 TWh in 2017 [24]) would always remain low and the greenhouse gas mitigation costs are medium to high compared with other renewable energy pathways [25]. In the course of this debate the advantages of biogas production largely got out of sight.

The Renewable Energies Act was amended again in 2012, 2014 and 2016/2017. Feed-in tariffs were gradually reduced, the so-called maize cap (an upper limit of cereals in new biogas plants of 60% from 2014 on and 50% since 2016) was introduced, the annual expansion of the installed electrical capacity was limited, a premium for flexible biogas production was implemented and a tender system in response to market trends was established [1,11,12,19,26].

After 2014, the previously steady increase of the Renewable Energies Act apportionment slowed down drastically, with 6.24 Eurocent per kWh in 2014 and 6.79 Eurocent per kWh in 2018 [18]. The area cultivated with silage maize has remained constant at ca. 2,100,000 ha since 2014 [27]. Likewise, the growth of the biogas sector largely ceased, with 8746 biogas plants in 2014 and estimated 9494 biogas plants by the end of 2018 [14]. From 2020 on, the guaranteed feed-in tariffs for existing biogas plants will start to expire depending on the year of commissioning, and already today many biogas plant operators have to take decisions on investing in the replacement of plant components or shutting down their plants.

However, anaerobic digestion is further needed, and even more in a future circular bioeconomy. It is a keystone for residue management and thus for biomass and nutrient cycling [28]. In addition, it is a renewable energy source capable of providing base load power as well as to flexibly balance demand and supply [29]. Under the changed legal and economic framework, a realignment of biogas production is urgently needed. Biogas production can be at the beginning of a new development if fundamental changes are managed. In this article we aim to sketch a vision of the future agricultural biogas plant and to discuss the required contribution of research.

2. The Vision of the Future Agricultural Biogas Plant

We envision:

- Future agricultural biogas production is an integral part of the circular bioeconomy. Residues are received from other production systems and returned to the biomass cycle. Other production systems are supplied with energy.
- Hence, the future agricultural biogas plant is primarily based on residues.
- The future agricultural biogas plant is flexible with regard to feedstocks, digester operation, microbial communities and biogas output. The digestion process is stable, susceptibility to disturbances is low.
- The future agricultural biogas plant is modular in design. Plant components are constructed separately and coupled on demand.
- The future biogas plant operates knowledge-based, information-driven and largely automated.
- Future agricultural biogas production becomes more efficient, achieves decreasing costs of production and creates supportive business environments.

3. How to Get There—the Required Contribution of Research

3.1. Systemic Multidisciplinary Research Approach

The pathway to the envisaged future biogas plant implies far-reaching changes in the entire biogas production system involving feedstocks, digester technology and operation, process monitoring and control, environmental and economic efficiency and business models. This change process also challenges researchers:

- to better understand the digestion process,
- to develop new tools for monitoring the digestion process,
- to advance with modelling the digestion process,
- to further explore the characteristics of residues and their effects on the digestion process,
- to identify and investigate new types of feedstocks,
- to further develop digester technologies and operation strategies,
- to identify and develop diverse links of biogas production with the supply of food, feed and biomaterials,
- to explore and reduce potential risks of cycling biomass via biogas plants,
- to assess environmental and economic performance of biogas production systems.

The wide scope of these tasks requires multidisciplinary research. Scientists from microbiology and molecular ecology, engineering, automation, data science, agricultural and environmental sciences and socio-economics need to join in a systemic approach. As in the biogas production system itself, these fields are connected with each other in research (Figure 1). Biomass characteristics determine digestion technology and process management. Together, they influence the system microbiology which determines the process results. Technology assessment investigates environmental and economic impacts of system components and the whole system as well as its interactions with other production systems.

The vision of the future agricultural biogas plants was developed in the specific context of Germany. Nonetheless the research needs discussed in the following chapters have a more general character and can be applied to other countries as well.

3.2. Knowledge-Based, Information-Driven and Largely Automated Biogas Production

3.2.1. Requirements

We imagine the future agricultural biogas plant to be operated on the basis of knowledge, information and automation (Figure 2). Knowledge-based means that the highly complex microbial process of anaerobic digestion is much better understood and that these basic insights are prepared for implementation in process monitoring and control. Information-driven means that feedstocks and digestion process are continuously monitored for physico-chemical and microbial parameters. The comprehensive knowledge and continuous information on the state of the digestion process form the basis for proceeding automation of plant operation. To cope with the increasing complexity in process control, the digestion process needs to be modelled. Future models take over the physico-chemical and microbial data from process monitoring, simulate options of process control, induce automated reactions or derive recommendations for the plant operator. Starting from these requirements, the next chapters deal with the needed progress in understanding, monitoring and modelling of the digestion process.

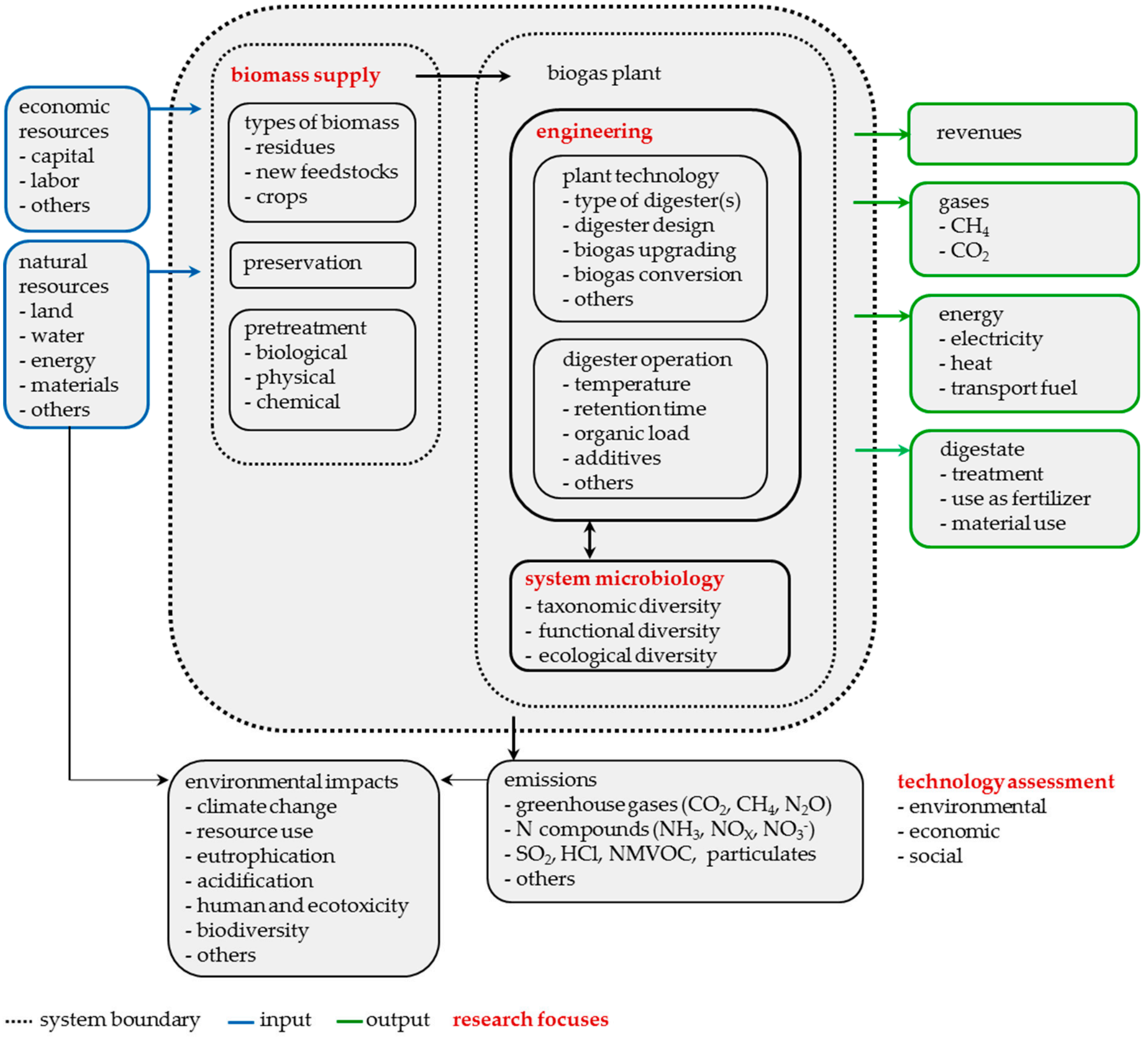

Figure 1. Systemic multidisciplinary biogas research (CO_2—carbon dioxide, CH_4—methane, N_2O—nitrous oxide, NH_3—ammonia, NO_x—nitrogen oxides, NO_3^-—nitrate, SO_2—sulfur dioxide, HCl—hydrogen chloride, NMVOC—non-methane volatile organic compounds).

3.2.2. Understanding the Digestion Process

Anaerobic digestion is a highly sensitive process exclusively carried out by microorganisms that are interdependently associated in a complex community and reside in a closed technical system with an environment controlled by the biogas plant operator [30]. Hence, it is crucial to understand how the biogas microbiomes respond to management measures and how this response affects the digestion process. This knowledge is needed even more with the required increase in feedstock diversity (Section 3.3) and process flexibility (Section 3.4). In future biogas plants the microbial communities will be subjected to frequently varying process conditions while ensuring an overall stable digestion process with low susceptibility to disturbances. Process disturbances have manifold causes with different underlying mechanisms (e.g., unfavorable process temperature, fluctuating nutrient availability, overload of the degradation potential, accumulation of process inhibiting metabolites, and many others) [30]. Digester design and operation have to be aligned after the requirements of the microbiome in the sense of a microbial-based management [31], which is a precondition to improve stability and efficiency of the digestion process.

Intensive research has provided new insights into the digestion process microbiology during the last two decades, still knowledge on the biogas microbiome is rather limited. Most of the microbiome members and even more their functions and ecological roles in the biogas process are still unknown [32–37].

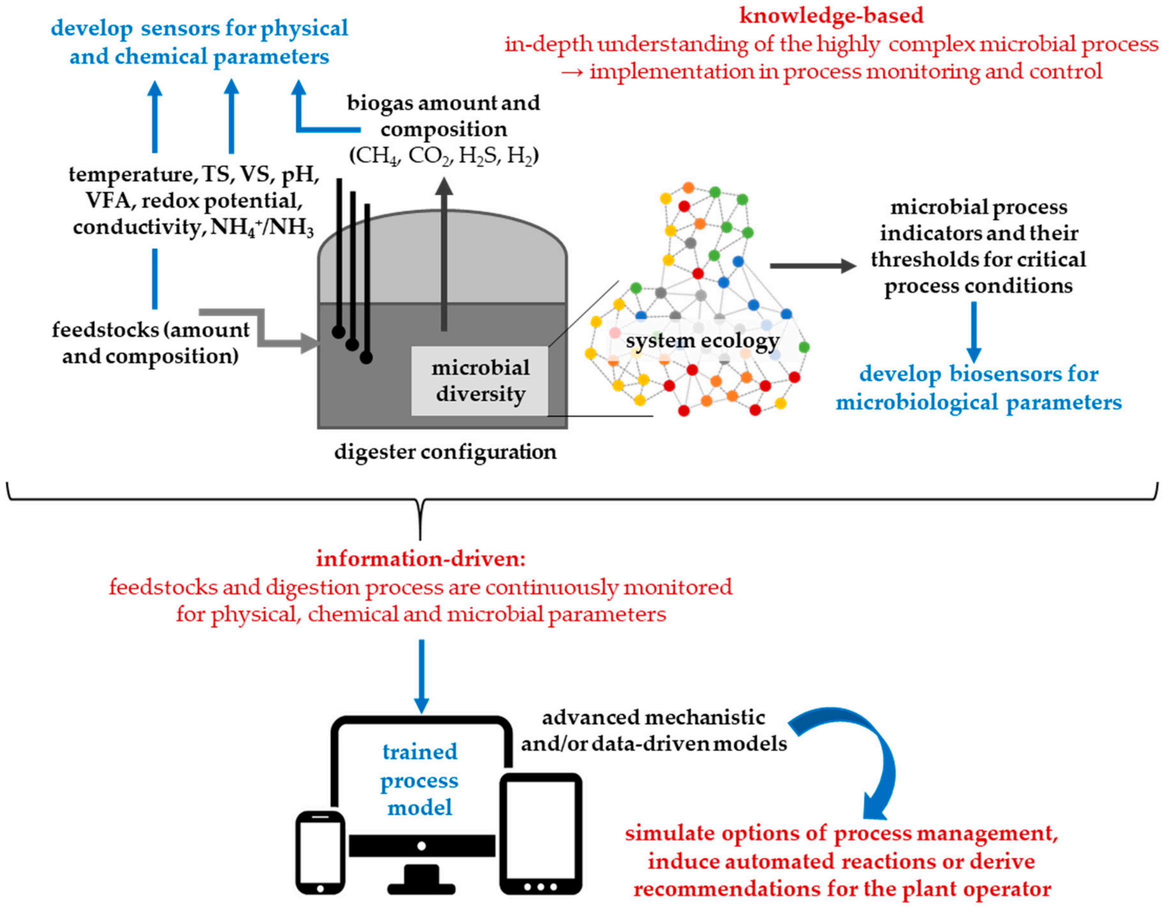

Figure 2. Knowledge-based, information-driven and largely automated biogas production (red font—research objectives, blue font—research demand, black font—research results for implementation). TS—total solids, VS—volatile solids, VFA—volatile fatty acids, NH_4^+—ammonium, NH_3—ammonia, CH_4—methane, CO_2—carbon dioxide, H_2S—hydrogen sulphide, H_2—hydrogen.

To achieve a knowledge-based microbiome management it is essential: (i) to identify the process-involved microorganisms at a species level (taxonomic diversity); (ii) to elucidate their metabolic potentials and actually realized processes (functional diversity); and (iii) to evaluate the fundamental ecological mechanisms which regulate the biotic and abiotic interactions, for example, adaptation to temporally changing environmental conditions, similar niche adaptations of co-occurring species, habitat affinities or differentiation between generalists and specialists (ecologic diversity) [37–41]. For this purpose, further research is needed in the following four topics:

- Single species: Efforts to isolate, cultivate and characterize known and yet unknown species need to be expanded. To explore the response of the microorganisms to varying environmental conditions, special emphasis has to be given on determining growth kinetics by up and down regulation of their metabolism through altering physico-chemical parameters such as temperature and nutrient supply. To capture the vast majority of not yet cultivable microorganisms [42], it is indispensable to develop new and more complex cultivation media that correspond with the natural living conditions of the microorganisms.
- Microbiome: New sequencing technologies such as Nanopore-sequencing [43] will allow for deeper exploration of the entire biogas microbiome. Nanopore-sequencing is supposed to elucidate the microbial diversity down to the species level by full-length sequencing of the 16S rRNA gene or the whole *rrn*-operon in a high temporal resolution [44–46].

- System ecology: To obtain an integrated view of all the existing biotic and abiotic relationships and interactions it is necessary to describe and understand the γ-diversity level of the biogas microbiome by using, for instance, co-occurrence network [38,47,48] or artificial neural network analyses [37]. This provides the opportunity to reveal if and how members of the microbiome are affected in the case of disturbances and can possibly be used for process monitoring (Section 3.2.3). Microbial communities can adapt to potentially unfavorable process conditions [49–51]. The question is how fast microbiomes acclimatize to changing environmental conditions or what kind of diversity level (high, medium or low regarding structure, function and ecology) is needed to withstand unfavorable process conditions. A certain level of functional redundancy (inhibited community members can be replaced by others with similar function) at any process stage seems to play a crucial role in ensuring a stable process [52].
- Assessment: develop new methods that assess the adaptability and resilience of microbial populations to specific environmental conditions delivering opportunities to derive microbial performance indicators.

Elaborating these advanced insights into the biogas microbiome will provide bases for innovations in process monitoring and control, digester design and operation and hence for improving the environmental and economic performance of biogas plants.

3.2.3. Monitoring the Digestion Process

Regular process monitoring is required to provide information on the general process performance and to recognize and respond to process instabilities/disturbances [53,54]. Today´s process control is based on technical and chemical parameters and on the experience of the biogas plant operators [39,40].

To ensure that the biogas plant is technically fully operational, a regular check of the technical equipment (e.g., digester technology, mechanic feeding, temperature regulation, stirring or pumping systems, combined heat and power unit) is common practice [53,54]. On-line analyses which are integrated in many of the existing biogas plants include the detection of the amount and types of the supplied feedstocks, temperature control, measurements of the pH value, the conductivity and redox potential, as well as the detection of the produced biogas amount, the gas composition and the generated electricity and heat. These parameters can be measured continuously at a daily level [53].

To comprehensively validate the process, a regular monitoring of significant chemical parameters (e.g., the chemical composition of the used feedstocks, the bioavailability and bioaccessibility of the anaerobically degradable compounds, the total solid (TS) and volatile solid (VS) content, the volatile fatty acid (VFA) concentration and spectrum, as well as the ammonium nitrogen and trace element content) is of high importance. Currently, most of the chemical process parameters still are measured by specialized laboratories. It is recommended to measure these parameters at least once per month [53]. Considering that anaerobic digestion is a highly sensitive and dynamic process, fast and frequently applicable detection methods would be desirable.

Therefore, current research efforts focus on the development of measurement technologies which allow a direct detection of relevant chemical indicators. Spectral techniques, such as Mid Infra-Red spectroscopy (MIR) or Near Infra-Red spectroscopy (NIRS), are most promising [53–56]. The major advantage of MIR is that relevant process variables such as TS, VFA, and NH_4^+ show distinctive peaks in the MIR spectrum, which enables to correlate peak intensity directly to actual concentrations [55]. Despite of the advances in infrared spectroscopic, NIR and MIR, regular on-line measurements are still not possible because these techniques are not sensitive and accurate enough for a correct detection of complex molecules and their real bioavailability/bioaccessibility. Moreover, infrared spectroscopic measurement systems are still far too expensive to be widely used in biogas plants [54]. However, more recent technical developments are under consideration. For example, there are efforts to develop microbial electrochemical sensors for the detection of VFA in the anaerobic digestion process [57,58] or the application of enzyme-based sensors which enables the simultaneous detection of ethanol, formate, lactate, acetate and propionate [59].

Monitoring the physico-chemical process parameters provides information on the abiotic conditions in the digester. As anaerobic digestion is a microbial process, its monitoring should be extended to supply direct information on the biotic state. This will allow for aligning digester operation with the microbiome and thus implementing a microbial-based management.

The methods available so far for monitoring the microbial community, such as cultivation and sequencing, are highly complex regarding sample preparation, conduct, and especially data evaluation and interpretation [37,38]. Therefore, their application is limited to research and highly specialized commercial service providers. There is a need to develop microbial detection methods that are fast, affordable and easily applicable directly at the biogas plant. To achieve this goal, microbial process indicators (i.e., single species or groups of microorganisms that reflect the current state of the digestion process and provide information about process stability or upcoming disturbances) have to be identified. In this context, studies that systematically induce typical stress situations for the biogas microbiome (e.g., changing nutrient availability and accessibility, unfavorable process temperature, accumulation of process-inhibiting metabolites) are highly valuable. Such approaches enable to identify thresholds for critical process conditions which are assigned to specific microorganisms and/or groups of microorganisms and/or ecological relationships. Based on this, the vision is to enlarge the knowledge about the potential to "train/coach/manage" the microbiome which is characterized by a higher adaptability and resilience against inconvenient process conditions. Finally, this will result in the ability to develop biosensors for a rapid and economical monitoring of the biogas microbiome.

3.2.4. Modelling the Digestion Process

To control, manage and optimize the biogas plant performance while ensuring stable and efficient biogas production, various process models have been developed [60,61], resulting in a better understanding of the process dynamics, providing optimization opportunities and improvement of digester performance [4,34,54,61,62]. The available models for anaerobic digestion systems can be divided into mechanistic and empirical/data-driven models [60,61]. Mechanistic models are based on biological, chemical and/or physical laws governing the behavior of a process while trying to consider in which manner individual parts of the system are coupled. In contrast, empirical/data-driven models are based on mathematical equations to describe the stochastic relationship of different parameters and variables using real measured process data.

The mostly used mechanistic model is the Anaerobic Digestion Model No. 1 (ADM 1) [60,61,63,64]. The ADM 1 as a dynamic model chiefly considers biochemical processes including the conversion of organic matter into carbohydrates, lipids, proteins and inert compounds as well as the four main process steps in terms of hydrolysis, acidogenesis, acetogenesis and methanogenesis including potential process inhibition by hydrogen and free ammonia [61]. The model is based on theoretically optimal reaction condition/kinetics and assumes a perfectly balanced mixture of all reactions, neglecting, for example, variations in the biodegradability/bioaccessablity of different chemical compounds [54,61]. Furthermore, the model is not able to consider the microbial diversity in its real taxonomic, functional and ecological complexity [34,61].

In the future biogas plant, a knowledge- and information-based prediction of the process is required which especially considers the microbiome performance. The aim is to take real data from the process monitoring, to simulate process control options, to automatically trigger control reactions or to derive recommendations for plant operation. To reach this goal, further research is needed on the following topics:

- to online measure process parameters, nutrient content, biogas production;
- to investigate growth rates and growth kinetics, gene expression and metabolic profiling, substrate utilization kinetics as well as the formed products of cultivable microorganisms;
- to profile the putative functions of uncultivable microorganisms by combining metagenome-assembled genome approaches [33,65] with genome-scale metabolic network reconstructions [66];

- to elucidate the entire microbiome at the species level using the most modern sequencing approaches in order to quantitatively describe and understand the biogas microbiome in its complexity and to predict its response to external and internal influences by using co-occurrence network analyses which provide an integrated view of all ecologic relationships between the occurring microorganisms in a given environmental matrix [37,38,47,48].

Process control and management using model-based approaches are still hampered by depicting the entire process in its real complexity, including the high variety of the chemical compounds of the supplied feedstocks and their bioavailability/bioaccessibility, the general process operation conditions, the microbial diversity, the biochemical process chain including the general process performance, the process output in terms of biogas yield and gas composition as well as the physico-chemical and biological characteristics of the digestate.

With the help of machine learning methods, models can be constructed that can predict process disturbances on the basis of temporal patterns in the observed parameters. Supervised classification methods construct such models from observations of stable process behavior and observations of process disturbances, with the goal of separating these two classes. Alternatively, one-class classification methods [67,68] can be used to characterize the typical stable process course from observations of stable processes only; any deviating patterns in future data are then labeled as anomaly and potential disturbance. The advantage of the latter approach is that also new, unknown process anomalies or disturbances can in principle be detected. The future use of such predictive models is complicated in practice by the fact that the available tools for detecting the microbial diversity are highly complex regarding sample preparation and especially data evaluation and interpretation [38]. Hence identifying microbial indicators by, for example, co-occurrence network analyses [38,47,48] or artificial neural network analyses [37] is a precondition for deriving informative input features for the development of predictive models. In order to reduce the cost and complexity of the needed microbiological measurements, cost-sensitive machine learning [69,70] is a promising approach. In cost-sensitive machine learning, input features of the models (e.g., the abundance of different microorganism) are associated with costs. The goal is to create a model based on a subset of input parameters whose total costs are as small as possible, while at the same time yielding a high predictive accuracy.

3.3. Diverse Feedstock Spectrum, Mainly Based on Residues

3.3.1. Requirements

With respect to feedstocks, the overall challenge for future biogas production is to shift from an easily degradable, largely energy crop-based and unchanging feedstock mix to a diverse feedstock spectrum that is mainly based on a wide variety of residues and complemented by promising new feedstocks and a limited proportion of crops that provide specific environmental benefits. General requirements to all these types of feedstocks are that their supply should not or to minimum extent compete with food production, avoid risks to humans and be environmentally and economically sound. Research is needed to further explore and improve feedstock characteristics and to develop or optimize supply chains.

3.3.2. Unlocking Residues

We here define residues as recent biomasses that accrue in production processes besides the main products, or remain after their use. The use of residues as feedstocks for anaerobic digestion reduces energy input, greenhouse gas emissions and feedstock supply costs since these items are allocated to the main products (except for residue transport and pretreatment) [71]. As a result greenhouse gas mitigation costs of residue-based biogas production are also low (e.g., [71]). Residue supply does not require agricultural land and hence usually does neither compete with food production nor impair biodiversity.

As essential as residue use is for future biogas production, anaerobic digestion vice versa is just as important for residue management. With further establishing the bioeconomy as a bio-based circular economy, organic residue flows will increase. Anaerobic digestion often is the only viable way to manage organic residues and to maintain nutrient cycles. In the future, for biogas plants the function of cycling residues might become equally or even more important as the function of energy generation.

However, residues pose a number of challenges since they:

- often have feedstock characteristics that make them difficult to handle in anaerobic digestion, (e.g., high contents of lignocellulose and substances that inhibit the digestion process);
- are of heterogeneous and fluctuating composition;
- may harbor risks such as possible contamination with pathogens, antibiotics, heavy metals, organic compounds;
- accrue decentrally in small amounts;
- are often difficult to collect and to store.

Manifold residues from crop production, livestock husbandry, landscape management, from food processing, food consumption and from biorefineries, as well as the organic fraction of municipal solid waste, may serve as feedstocks for anaerobic digestion. Hence, further studies are needed to characterize these diverse residues, to investigate their effects on the process and to find solutions for difficult feedstocks.

Residues from livestock husbandry are abundant and common feedstocks in biogas production [72–75]. Biogas production from liquid and solid manure does not only contribute to energy supply, but is also an essential measure of integrated manure management strategies to reduce environmental impacts [76,77]. Methane yields depend mainly on animal species [78,79] and further on their type of use, sex, age and diets [80–82]. The potential for influencing feedstock characteristics seems small. Making solid manure available would largely extend both the biomass potential and the environmental benefits, however it faces obstacles due to high contents of lignocellulose in the case of solid cattle and pig manure and high nitrogen concentrations in the case of poultry manure. Hence, research is done and further needed on pretreatment of solid manure and avoiding ammonia inhibition when using poultry manure [72,83]. Since livestock residues accrue in different amounts, research is required to design supply chains and biogas production facilities from household scale to large central biogas plants [84].

Residues from landscape management—i.e., herbaceous biomass from semi-natural grasslands and from the maintenance of river and roadsides—are a potential feedstock for anaerobic digestion, whose utilization could provide highly desirable synergies between bioenergy production and conservation of biodiversity. However, poor ensilability and digestibility due to late harvesting dates [85–87] and high supply costs due to often low biomass yields, difficult harvesting conditions and large transport distances [88–90] still limit practical implementation. While unfavorable feedstock characteristics may be regarded as well-known, ongoing research on preservation, pretreatment, environmental and economic performance [91–96] needs to be continued.

Residues from the entire food supply chain (production, processing, distribution, storage, and sale), as well as the organic fraction of municipal solid wastes (OFMSW) (e.g., organic residues from households, kitchens, restaurants, factory lunch rooms and supermarkets, as well as leaves, grass clippings, or yard trimmings), are valuable feedstocks for anaerobic digestion [2,97–102]. Currently, in Germany only 20–30% of the yearly 9.8 Million tons of organic household residues are treated in anaerobic digestion plants [11]. These feedstocks are highly variable as their composition differs between rural and urbanized areas and undergoes seasonal changes [97–99,101,102]. Before they can be fed to an anaerobic digester, pre-processing is required, for example, to remove plastics, metals, glass, and other impurities, to reduce/homogenize the particle size, to improve the solubilization of the organic material and to eliminate pathogens [97,98,103,104]. In Germany, thermal pretreatment for hygienization is mandatory per legislation [105]. However, the chemical variability of these feedstocks remains high and is the major challenge for anaerobic digestion. For example, fruit and vegetable wastes, with their high contents of volatile solids, often lead to an acidification [102,104], while slaughterhouse or dairy residues with their high protein and lipid contents carry the risk of accumulating process-inhibiting metabolites such as ammonium/ammonia, hydrogen sulphide or long chain fatty acids [102,103]. To avoid these problems, co-digestion of organic waste with animal manure or sewage sludge or the usage of multi-stage anaerobic digestions systems are commonly applied [99,101,102]. Due to the high variability of organic waste, future research should consider a comprehensive chemical feedstock characterization to combine them in a suitable proportion with other feedstocks [97,98,101,102].

The future agricultural biogas plant needs to provide solutions for increased degradation of less digestible residues of different types and compositions (Section 3.4.2.) and minimize risks such as the distribution of pathogens and contaminants.

3.3.3. Aquatic Biomass

Besides organic residues, aquatic plants and algae were discovered as potential feedstocks for biogas production in recent years. Water-based biomass is generally considered as advanced or third generation feedstock [106] due to several advantages compared with terrestrial biomass, including high biomass yield potentials caused by rapid growth and high photosynthetic efficiency, high diversity, no need for fertile agricultural land for cultivation and thus, no direct competition with food production [107–111]. The very low lignin contents of aquatic biomass provide easy degradability during the anaerobic digestion process if no other recalcitrant components appear [106,108,109]. Besides, algae cultivation can be favorably integrated with biogas production. Unutilized CO_2 of the biogas can be used as a carbon source for biofixation by algae, and digestate can be applied as nutrient source [108,111,112]. Macroalgae and aquatic plants can occur as waste biomass in natural water bodies during eutrophication or during weed control measures in waterways [113,114], however, this resource is locally restricted and rather limited. Thus, cultivation of aquatic plants or algae would be necessary to supply significant amounts.

Biogas production from aquatic biomass has been technically proven, but substantial research is still required for up-scaling and the development of economically viable solutions. The key challenge lies in the reduction of costs for aquatic biomass production as they are currently much higher than costs for land-based crop production [107,115]. This involves the need for the development of low-cost but highly efficient photo-bioreactors, cultivation and harvesting methods, including inexpensive technologies for concentration of dilute microalgae suspensions at harvest. Some promising approaches for cost reduction include the combination of cultivation with wastewater treatment for nutrient supply [115,116], additional use of aquatic biomass for extraction of high-value compounds prior to biogas production [106,115,117], or the integration with advanced cultivation systems such as integrated multi-trophic aquaculture [109]. Further research is necessary to improve the methane production potential and anaerobic conversion of aquatic biomass through selection of appropriate species and optimization of cultivation conditions for high gas yields, and the development of strategies to increase process stability and to avoid inhibition which may be caused for instance, by high protein, lipid, sulphur, polyphenol, halogen, or saline concentrations in some algae or aquatic plants [115,118]. As the chemical composition and suitability for biogas production of macroalgae and aquatic plants vary with season, optimal harvest times and methods for preservation and storage to allow year-around feedstock supply also need to be identified [119].

3.3.4. Crops

For the last two decades, crops have enlarged the feedstock basis and increased methane yields [120,121]. Although there is a wide variety of crops actually or potentially to be used for anaerobic digestion, silage maize has become the predominant energy crop in biogas production due to its high methane and biomass yields [122].

Crops dedicated to the production of biogas are subject of an ongoing societal and scientific discussion about environmental efficiency and competition with food production. Their cultivation requires resources, causes emissions and may lead to direct and indirect land use change (e.g., [13,123,124]). Hence, future biogas systems should limit the use of crops to those which do not compete with food production and generate specific added environmental values, such as fostering biodiversity and soil fertility.

Worldwide, there is a variety of options to cultivate crops dedicated to biogas production on lands where food and feed crops are not grown due to unfavorable natural or economic conditions, such as marginal lands [125,126], semi-arid lands [127], degraded lands [128], surplus grasslands [129] or former cutaway peatlands [130]. Here, energy crop cultivation is often the only way to keep or make the land suitable for agricultural use and simultaneously maintain or improve the ecological status.

In Germany, the research focus is moving from primary energy cropping towards diversification and environmental upgrading of existing food and feed cropping systems with additional crop species serving as feedstock for anaerobic digestion. Mixed cultivation, such as inter- and double cropping [131–133], integration of flowering crops in crop rotations [134] or the use of perennial crops [133,135], offer numerous chances for increasing biodiversity of flora and fauna and for soil carbon sequestration. Promotion of flowering crops is of vital importance to maintain pollinators in the agricultural landscape. Therefore, novel plants (e.g., cup plant, *Silphium perfoliatum* L.) [136] or wild flower mixtures [137,138], as well as flowering catch crops [134], should be integrated, with the latter concurrently contributing to the reduction of nutrient losses and the improvement of soil quality [136,139].

Permanent grasslands present a considerable potential for biogas production, greenhouse gas emissions reduction and biodiversity preservation [140–143]. According to current estimates, surplus grasslands, which are no longer used for livestock husbandry, can supply feedstock for regional biogas production [91]. To which extent the use of grass biomass for anaerobic digestion can be increased will largely depend on prevailing regional economies and coming innovations. In future, regional analyses are required to identify the regions where grassland is available for providing biogas feedstock. Another research demand is to optimize grassland management for anaerobic digestion, for example, to identify suitable grass species, fertilization regimes, harvesting frequencies and periods [144–146] Even more importantly, it seems to find suitable ways for improving feedstock characteristics of biomass from more extensively managed grasslands by ensiling and pretreatment [147,148].

3.3.5. Gases

Another type of feedstock for potential future application in biogas production are gases. Hydrogen and carbon dioxide can be directly fed into the biogas digester and converted into methane by hydrogenotrophic methanogens. In this process, hydrogen is produced from surplus renewable energy by electrolysis, and CO_2 can originate from different residue streams such as from industrial processes, bioethanol plants, biogas plants or wastewater treatment [149]. The use of such power-to-methane concepts has potential for system integration, however, several challenges associated with the gaseous substrates need to be addressed. Changes in H_2 partial pressure and pH due to addition of H_2 to the anaerobic digestion process can lead to excess organic acid formation and process disturbances [150]. Owing to the poor solubility of H_2 within the liquid phase of the anaerobic digester, gas-liquid mass transfer has been identified as the main limiting factor and mass transfer limitations need to be further reduced for improved gas conversion and productivity [151]. A promising approach to face this issue is the development of special biofilm reactors with a reduced liquid phase and intense gas-liquid surface contact [152,153].

3.4. Flexible and Modular Biogas Plants

3.4.1. Requirements

While most biogas plants today are designed for constant operation, future biogas plants are required to become more and more flexible with regard to all three stages: input, process and output (Figure 3). On the input side, a much more diverse, varying and difficult to degrade feedstock spectrum has to be considered. On the output side, a flexible biogas production on demand is required. In between, digester technology and operation has to be designed to be more flexible, to adapt to both varying input and output.

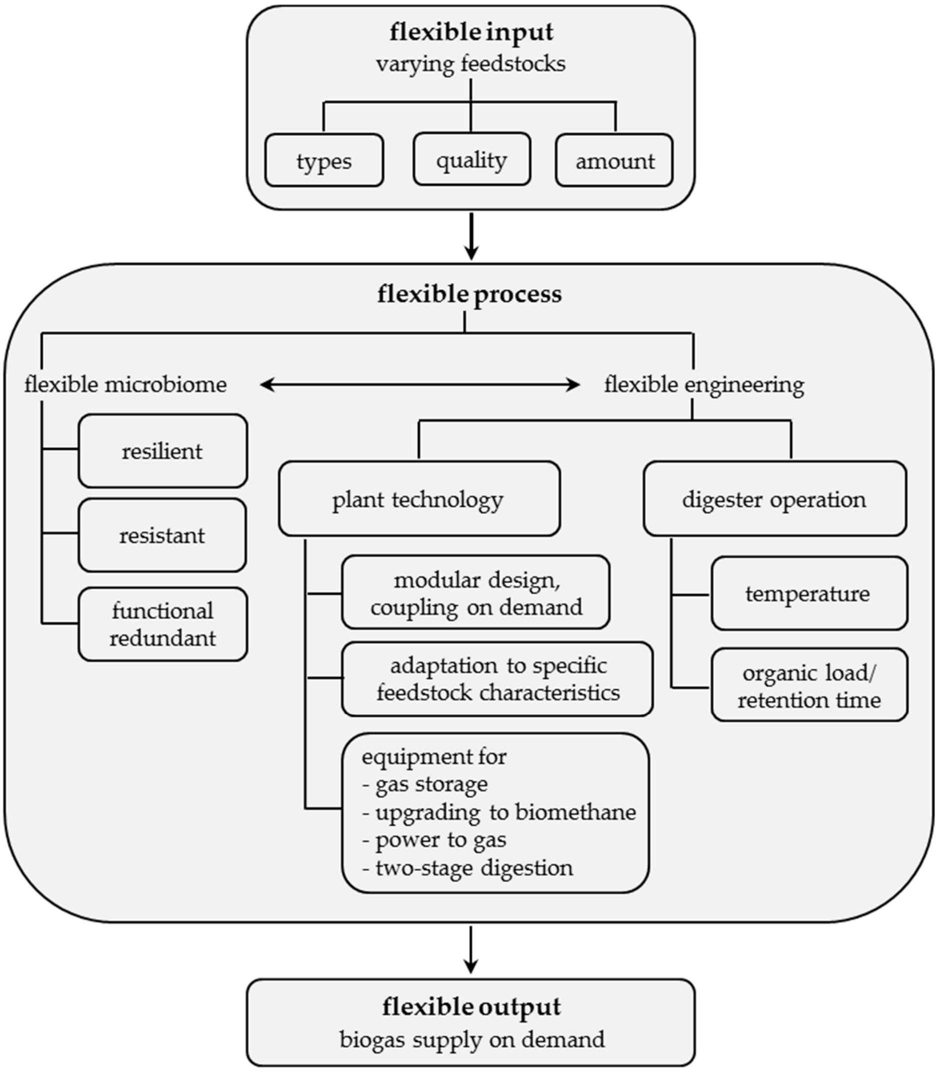

Figure 3. Components of flexible biogas plants.

3.4.2. Engineering for an Increased Use of Residues and Novel Feedstocks

Although the biogas microbiome is able to degrade a broad spectrum of organic feedstocks, process operation of existing biogas plants in Germany is traditionally based on steady feeding of constant feedstock mixtures, mainly crop silages and liquid manure, and process technology is usually designed to digest feedstocks with predefined characteristics [11]. With transition towards an increasing use of residues higher feedstock flexibility will become necessary, since residues often occur in fluctuating amounts, quality and composition (Section 3.3.2). This will require the development of adapted digester systems and technology which is robust and suitable to handle variable feedstock characteristics.

Agricultural residues such as straw, materials from landscape management, or solid manures feature high total solids (TS) and fiber contents and slow degradability [154]. For digestion of these types of feedstocks, adapted hydraulic retention times and operating conditions, a robust feeding technology, and stirring units that can effectively agitate feedstock mixtures of higher TS concentrations in wet digestion systems, for example, slowly rotating axial stirrers, are inevitable [120]. Changes in viscosity characteristics of the digester content and increased wearing of technical components need to be considered [155].

Pretreatment technologies for positive effects on rheology, increased degradability and gas production, and a reduction of the necessary retention time will become increasingly important. There is a multitude of pretreatment techniques decomposing the biomass physically (mechanical, thermal, baric, ultrasound, microwave), chemically (acid, alkali) or biologically (composting, ensiling, enzymes, fungi) [148,154,156–158]. Mechanical and enzymatic disintegration methods, in particular, have largely evolved within recent years, but further research is required to identify the most effective pretreatment techniques for different types of biomass, to upscale them from lab to pilot to full scale and to consider net effects on energy yield, greenhouse gas emissions and profitability. So far, only a few studies allow for a comprehensive assessment of pretreatment techniques by considering net effects at full scale and along the whole biogas production chain [159–161].

Solid-state anaerobic digestion techniques (plug flow reactors, leach-bed reactors) offer advantages in handling high-solids feedstocks since they can cope with the digestion of fibrous materials, high lignocellulose contents, and impurities [152,162,163]. Yet, bioreactors for high-solids anaerobic digestion are so far rarely applied at farm-scale [155]

Potential contents of inhibiting substances in waste and residual materials are another challenge. In general, two-stage processes with separation of the hydrolysis/acidogenesis and acetogenesis/methanogenesis step are more stable and robust against inhibitors and changes in feedstock composition than single-stage processes [154,164]. They can yield enhanced gas production and reduce the retention time of solid materials [154]. The most developed reactor technology for two-stage digestion of solid materials are leach-bed-systems, however, they have the disadvantage of being operated in batch or sequential batch mode which is associated with a labor-intensive procedure for opening and restart of the anaerobic digestion process, unsteady gas production and higher greenhouse gas emissions [120,151]. Large potential for future application is seen for continuous two-stage high-solids systems that operate with little moving parts and are characterized by low internal electricity demand [165,166].

Some organic residues, such as industrial, municipal or agricultural wastewaters, liquid manures and side-streams of other biological conversion or down-streaming processes, as well as alternative feedstocks such as harvested suspensions from microalgae production, are characterized by high water and low total solids content. In continuously stirred tank reactors this leads to either high reactor volume requirements or low hydraulic retention times which can result in wash-out of slowly growing microbes, and induce process instabilities [41,167]. An effective solution to prevent microbial wash-out is the retention and enrichment of active biomass within the reactor by sedimentation, retention of self-aggregated granules, or immobilization through biofilm growth on carrier materials [104]. In addition, the growth of microorganisms in granules or biofilms provides benefits for syntrophic interaction and a higher resistance to environmental changes and harmful substances and, thus, higher process stability [168]. Numerous reactor concepts for low-solids anaerobic digestion with biomass retention have been developed, but are mainly used for industrial and municipal wastewater treatment at present.

Another approach for enhanced feedstock flexibility is the development of modular systems with components that can be combined or activated on demand. This could comprise components for pretreatment, for elimination of inhibiting substances, different reactor stages such as separate hydrolysis or ex-situ methanation for conversion of gases, treatment of digestate and the processing or upgrading of produced biogas. Some of these parts can be easily included as modular components in biogas plants (e.g., pretreatment or digestate treatment modules [169]), others are still under investigation or need to be developed (e.g., modules for removal of process inhibitors, such as ammonia stripping or magnesium ammonium phosphate precipitation [170]). Activation of modular components on demand requires feedstock and process surveillance and reliable control systems.

Residues that occur in a decentralized, seasonally and process-dependent manner could be digested by mobile biogas plants. Mobile biogas plant applications would need solutions for energy self-sustaining operation, transportation, and periods to stay idle and reactivate afterwards. Some approaches in this direction exist already [171,172], but mobile biogas plants are not yet state-of-the-art. Considerable research is still necessary to develop commercial-scale applications for flexible feedstock digestion and modular and mobile biogas plants.

3.4.3. Biogas Supply on Demand

The power supply system in Germany faces the challenge to meet intraday, daily, and seasonal variations in electricity demand, and, in addition, to balance the increasing share of power supply by the fluctuating renewable energy sources, wind and photovoltaic. In 2017, renewable electricity reached 36% of the gross electricity consumption with a contribution to the total renewable electricity of 48.9% from wind and 18.2% from photovoltaic [173]. To ensure grid stability and react to fluctuations in electricity demand and electricity supply, a share of controllable electricity production is indispensable. Biogas production has the advantage of being highly predictable and independent from variable weather conditions. It can provide base load and has considerable potential to balance intermittent electricity supply [174], and thus, holds a key role among the renewable energy systems.

Flexible power supply from biogas can have the aim to either realize periods of higher and lower electricity generation, alternating periods of variable duration with and without electricity generation, or short-term intraday changes in electricity generation according to external request. Requirements on flexibility differ depending on the targeted balancing service. Regular and cyclic changes in electricity generation are easier to schedule and apply to biogas plant operation than irregular short-term variations. Several concepts exist for the technical implementation of demand-driven biogas supply:

- Enlargement of on-site biogas storage capacities allows the storage of surplus biogas during periods of negative balancing power demand and additional biogas utilization in combined heat and power (CHP) units during periods of positive balancing power demand. No changes in digester operation are required. Although this option is comparatively easy to realize in existing biogas plants, additional gas storage installations are expensive and capacities might be limited by legal regulations [175,176]. Expansion of on-site storage capacity is most suitable for small biogas plants and balancing of short periods without biogas utilization [176].
- Increased feeding-in of biomethane into the natural gas grid instead of on-site combustion with combined heat and power units. The natural gas grid already features large storage capacities [177]. As the feeding-in of biomethane into the natural gas net allows for a conversion into electricity at larger scale, combined cycle gas turbines with conversion efficiencies of above 60%, electric efficiencies may increase compared to the local, small scale power generation units that are currently common [149].
- Variable feeding (feedstock amount and composition) to the digester or an adapted temperature regime can regulate the amount of methane produced within the biogas plant [49,51,178–181]. This option reduces necessary investments for flexibilization [176], but requires a resilient microbiome (Section 3.2.2.) as well as reliable process monitoring and control (Section 3.2.3). Rapid changes in feedstocks and/or temperature bear the risk of process disturbances [30], limits of flexible feeding need to be well known and considered. Model-based predictive process control [180] (Section 3.2.4) and specific digester configurations [182] can increase process

stability and help to enhance flexibility, while maintaining stable conditions and thus need to be further developed.

- Another option for flexible gas formation is the separation of the hydrolysis/acidogenesis from the acetogenesis/methanogenesis stage in the two-stage processes, which enables the production of an effluent enriched with organic acids that can be stored and rapidly converted into methane on demand. Different configurations of two-stage reactor systems have been suggested for demand-driven biogas production, combining a continuous stirred tank reactor or leach-bed reactor as the first stage with an high-performance reactor such as an upflow anaerobic sludge blanket or fixed-bed reactor as the second stage [165,176,183]. Disadvantage of two-stage systems is their higher complexity which also leads to higher investment costs. Technological and financial effort is required to apply this option for demand-driven biogas production to existing biogas plants.
- Power-to-gas technologies can be used to store surplus renewable electricity by converting it into hydrogen via electrolysis of water. On demand, the hydrogen can be combined with CO_2 and fed to the anaerobic digestion process to biologically convert these gases into methane [149]. This conversion may take place within an existing biogas reactor (in-situ) or in an external reactor (ex-situ) with the latter being more flexible regarding the adjustment of optimal process conditions and adapted reactor configurations [150]. Power-to-gas technologies are still in a developmental stage, a major challenge lies in the up-scaling of the developed reactor systems and technologies to commercial scale.

Since biogas plants have been built under the premise of steady gas production and a regular and consistent feeding with almost constant feedstock mixtures during the last decades, research into flexible biogas production is still in an early stage. To implement the above mentioned options for demand-driven biogas production at large-scale, research is necessary within the near future with focus on: (i) the development or adaptation of plant components to flexible gas production and utilization such as the feeding and agitation technology, the combined heat and power unit, the gas storage and filling level measurement; (ii) enhancement of process monitoring and control technologies; (iii) identification of kinetics of gas production from different feedstocks and limits of flexible feeding depending on process parameters; (iv) development of reactor design and technology that can provide high feedstock flexibility, efficient conversion and high process stability; (v) identification of strategies to establish resilient microbiomes; and (vi) development of process prediction models.

3.5. Integrated Biogas Production in a Circular Bioeconomy

3.5.1. Requirements

The transition to a bioeconomy requires that in future products are less based on fossil resources, but instead are produced from biogenic resources. To decrease the reliance on fossil resources, substance cylces are closed, nutrients are recycled, and biomasses are used efficiently to produce food, feed, biochemicals, biomaterials, biofuels, electricity and heat. Often this will mean that biomass is not exclusively produced for one purpose, but utilized in longer production chains than today.

While the initial target of implementing biogas production in Germany was the provision of renewable energy, we envision that in future the functions of biogas will be much more versatile. Anaerobic digestion may become an integral part of the bioeconomy and fulfill three basic functions: (i) it helps to produce essential chemical substances; (ii) it harvests the energetic potential of residues; and (iii) contributes to recycling of nutrients and organic carbon.

As there is a multitude of options to use residues and to couple the production of food, bioenergy and biomaterials, favorable pathways have to be identified.

3.5.2. Coupling Anaerobic Digestion with Other Production Systems of the Bioeconomy

Anaerobic digestion can be combined with other production systems of the bioeconomy through direct use of the produced gases, integration into biorefineries, bioenergy supply and digestate utilization (Figure 4). With growing biomass flows, the necessity to consider and reduce risks increases.

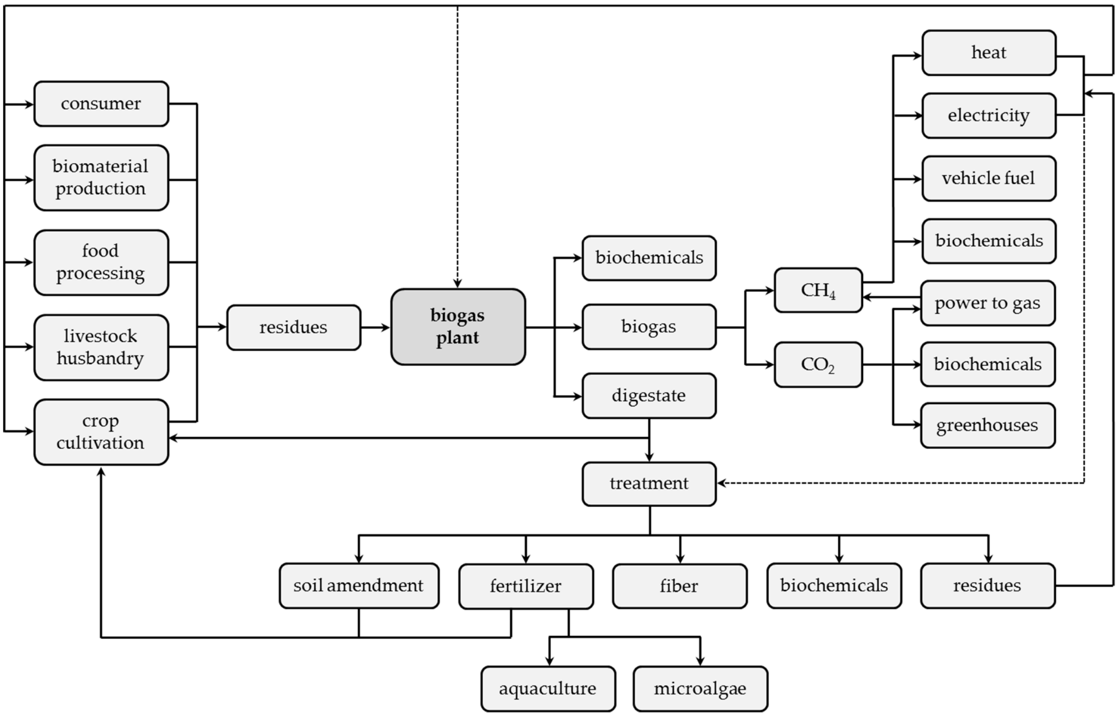

Figure 4. Biogas plant in bioeconomic systems for the integrated production of food, bioenergy and biomaterials (arrows indicate biomass and/or energy flows, dashed arrows indicate in-process energy flows).

Anaerobic digestion produces the gases CH_4 and CO_2 which can be utilized directly for other processes. CH_4 can not only be used as an energy carrier, but can also function as a feedstock for the production of the biopolymer polyhydroxybutyrate (PHB), which after usage could be degraded back to biogas [184]. CO_2 can be used for power-to-gas solutions (Section 3.4.3.), as a carbon source for chemical production (methane, methanol, polyoxymethylene) [185,186] or to enrich CO_2 concentrations in greenhouses to increase vegetable yields [187,188]. CO_2 sequestration is an integral part of bioenergy with carbon capture and storage, one of the key negative emission technologies suggested to limit global warming to 1.5 °C [189,190].

Biogas plants can be a crucial part of future biorefinery solutions. Residue biorefineries use, for example, the organic fraction of municipal solid waste to obtain biochemicals such as polyhydroxyalkanoates [191] or lactic acid [192] or lignocellulosic biomass such as straw to generate enzymes, biohydrogen or bioethanol [193,194]. Green biorefineries convert herbaceous biomass into value-added products such as feed rich in proteins and energy, lactic acid to produce biopolymers, fiber, organic fertilizer and bioenergy [129,195,196]. In these biorefineries, the remaining solid fractions still offer substantial biogas potential [197], and the digestate can be treated further to produce nutrient-rich fertilizers and stable soil amendments [3,198]. Residues from industrial crop cultivation and processing can also be used as feedstocks for anaerobic digestion [199]. Another option is to separate metabolic intermediates of the anaerobic digestion process such as volatile fatty acids to produce biochemicals [200]. In a future bioeconomy, anaerobic digestion could also gain in importance for the degradation and energy recovery from bioproducts after their use [201].

Biogas plants help to close substance cycles by recycling nutrients and organic carbon through treating organic residues and producing valuable digestates that can be used as fertilizers, for biomaterial production or further conversion into energy [202]. Usually digestates are applied to agricultural land where they return organic carbon back to the soil [203,204] and replace mineral N, P, K fertilizers achieving similar crop and grassland yield levels [205,206]. Fertilizer use of digestates is also possible in aquaculture [207] and microalgae cultivation [117,202,208]. Alternatively, digestates are considered for obtaining biochemicals such as chitin [209] or fiber [210]. Depending on utilization pathway, regional conditions and economic feasibility, digestate treatment by ammonia stripping, chemical precipitation, mechanical, electro-chemical or membrane solid-liquid-separation, drying, pyrolysis or hydrothermal carbonization can be appropriate to recover nutrients, remove particles and reduce transport expenses [211].

With the growing biomass flows in a circular bioeconomy, potential risks need to be considered and minimized. Hazardous components contained in feedstocks such as human, animal and plant pathogens, antibiotics, antimicrobial resistencies, organic pollutants, heavy metals and weed seeds might be spread with the application of digestates. On the other hand, it can be expected that these components are partially or completely eliminated during the digestion process. So far, most publications confirm the latter. Usually, biological degradation during anaerobic digestion reduces hazardous components to various extents [203,212–217]. However, in some cases persistent pathogens, increased heavy metal concentrations or eco-toxic effects were observed [213,216,218,219]. Elimination rates depend on the type of elements/compounds/pathogens, on feedstocks, digester operating conditions and digestate treatment. Hence, further research is needed to design feedstock pretreatment, digester configuration and operation and digestate treatment for risk minimization.

A further large potential to improve the overall efficiency of biogas production is offered by intelligent heat use from cogeneration. Even though the use of heat has increased in Germany in recent years as a result of stricter regulations, currently only about 56% of the external heat is utilized [11]. Heat usage can contribute to many processes within the bioeconomy, such as barn and greenhouse heating, beer brewing, drying of cereals and digestate, aquaponics in fish production food processing industry or biorefinery processes [188,220–222]. Excess heat can also be used for thermal pretreatment of feedstocks to enhance methane yields and thus improve the energy balance [156,159]. In a growing bioeconomy, the decentral heat demand for such local production processes can be assumed to increase.

Future biogas plant concepts need to explore the manifold potential linkages with the bioeconomy and to realize the most suitable ones under the individual local conditions of feedstock availability and demand for the products of anaerobic digestion.

3.5.3. Learning from Environmental Impact Assessments of Biogas Production

Life cycle assessment (LCA) has been used extensively to study biogas production systems [223]. The environmental impacts of biogas systems depend on many factors with a wide range of results mainly influenced by type and mixtures of feedstocks, way and percentage of utilizing the produced energy and digestion technology [71,224]. Regional variation appears even within small areas [225]. Most studies report environmental benefits for biogas systems, however, to very different extents and not for all systems in all impact categories. The variety of LCAs on different aspects of biogas production can provide hints that deserve consideration in the future sustainable use of biogas in Germany:

- Future biogas needs to be based increasingly on residues, and to a lesser degree on energy crops exclusively grown for biogas production, as these are often responsible for a main fraction of greenhouse gas emissions [71,226,227]. Plants mostly based on animal manures have higher environmental benefits than those including energy crops [228].
- Treating animal manures in biogas is advantageous over direct use as a fertilizer due to the reduction of emissions from storage and additional energy gain [229–231]. To exploit these unused potentials should therefore be a priority.

- Transport distances of feedstocks need to be low, especially for liquid or bulky feedstocks with relatively low energy content [224].
- Digestate management is important. To avoid greenhouse gas and ammonia emissions, eutrophication and acidification, digestate stores have to be covered [71,226,232], transport distances to the field need to be low [224] and digestate should be injected into the soil or incorporated immediately after at field application [233]. Appropriate digestate treatment can further improve the environmental performance [233].
- Heat utilization is of great importance. Increased heat usage from cogeneration can reduce environmental impacts [188,228,234], while low heat usage in combination with longer feedstock transports, can even result in biogas plants with negative impacts [235]. The importance of heat usage also explains why biomethane feeding into the gas grid with subsequent high heat usage can be advantageous over local combustion with low heat usage [236].
- Biorefinery concepts (Section 3.5.2) can increase the environmental efficiency of the processes involved [3,237], but feedstock selection is equally important since even similar feedstocks such as alfalfa or clovergrass can have substantially different impacts [195].
- Compared to other options that generate electricity from residues biogas is usually among the options with the lowest environmental impacts. However, depending on specific conditions, and especially for relatively dry substrates with lower nitrogen contents, combustion to generate heat and electric energy, or material use can also be a viable option [238,239].

First and foremost, life cycle assessments often rely on rated general parameters, such as the globally applicable emission factors from [230,232,240,241]. However, measured emissions can differ substantially from earlier assumptions and also vary by an order of magnitude [242]. This highlights: (i) that the data basis for LCA needs to be improved by measurements, particularly when new feedstocks and technologies are considered; and (ii) that an in-depth sensitivity and uncertainty analysis is important, but so far not very common [71,243].

Furthermore, direct and even more indirect land use change is often not accounted for, but can substantially change the overall environmental impact [123,244]. It is discussed whether and how it can be considered [245–248]. Even though the relevance of land use change will decrease with a reduced use of energy crops, potential effects could occur further on if residues used for biogas production compete with livestock feeding [249].

When novel feedstocks are identified and novel technologies are being developed for future biogas systems, a continuous research demand generally exists for the environmental impact assessment of single process steps and whole biogas systems. The methodological challenges in environmental impact assessments of biogas systems as discussed above need to be included in the research agenda.

3.5.4. Business Environments and Business Models

In the past, the development of agricultural biogas production as a socio-technical system has been influenced to a great extent by socioeconomic factors such as public perceptions, acceptance, contributions to rural livelihoods and capacity development [250]. Socioeconomic factors are likely to play a decisive role for the performance of the future agricultural biogas plants, besides techno-economic and biophysical factors. A major challenge for enterprises and researchers is the development of business models and business environments that contribute to a viable and accepted production.

To be successful in the future, agricultural biogas production will need business environments characterized by the alignment of strategies, collaborations, processes and steering structures. This requirement may itself require a business environment that is eager to learn and innovate. While these factors are to a great extent out of the influence of the biogas enterprises themselves, empirical evidence shows that biogas projects can contribute to shaping their business environments mainly through participatory processes and higher social embeddedness [250,251]. Increasing the participation of business partners and customers in the business at local levels may contribute to the overall goals of increasing adaptiveness to changing business environments and becoming less dependent on exogenous factors. Increasing the capacity of shaping its own business environment will be particularly relevant in futures were general landscapes for agricultural biogas production are less supportive.

Beside the business environment, the business models for agricultural biogas production need to be developed mainly by the biogas entrepreneurs themselves [252]. To ensure a competitive cost structure, entrepreneurs and researchers need to consider how the value propositions and key activities can be aligned in a better way with the key resources and key partners. The entrepreneurs of the future biogas plants may be able to reduce investment risks and transaction costs by establishing long-term and reliable customer relationships based on consistent segmentations of their customers. Revenue streams will be sustainable only if the proper channels are chosen to reach existing and new customers. These aspects need to be well aligned within the business models. Evidences from other sectors highlight the need for a variety of solutions for business models in the bioeconomy [253].

Financial incentives for biogas production in Germany, such as the Renewable Energies Act, created little incentives for capacity building in the field of business models and business environments development [254]. The present changes in the general landscape for biogas production, as well as the potential technical innovations, require additional capacities at the level of the individuals, organizations and societies for developing business models and managing business environments. In view of the increasing diversity and complexity of agricultural biogas production including a high diversity of feedstocks and feedstock sources as well as a high degree of flexibility, modularity and integration of biogas production, capacities are needed to test and adapt the business model solutions to the circumstances of each specific biogas plant in the future.

3.5.5. Modelling Biogas Systems

As discussed before, biogas systems show a broad variability with regard to feedstocks, digester configuration and operation, utilization pathways for the products and potential linkages with other production systems of the bioeconomy. On-site solutions for biogas plants must be tailored to the specific local conditions, technically viable, environmentally sound and economically feasible. The environmental and economic efficiency of biogas systems is influenced by many factors. To identify the most suitable concepts, a multi-criteria assessment of the multiple options to design biogas systems is necessary.

The high complexity of biogas systems requires system modelling and simulation for their comprehensive understanding, assessment and individual design. So far, modelling of biogas systems refers to selected details such as comparing feedstocks, biogas conversion or digestate treatment pathways (Section 3.5.2). Developing a modular, extendable biogas systems model covering all steps of the process chains from biomass supply over digestion to gas and digestate use with their inputs, outputs and emissions, linking biogas with food and biomaterial systems and quantifying environmental and economic impacts under varying conditions is a task still to be solved.

4. Summary

Future agricultural biogas production in Germany requires fundamental changes along the whole production chain, from feedstock supply over biogas plant technology to product use. These challenges require comprehensive basic and applied research in a multidisciplinary system approach.

To control the microbial process of anaerobic digestion it is crucial to better understand how the biogas microbiomes respond to management measures and how this response affects the digestion process. Techniques need to be developed to continuously monitor feedstocks and digestion process for physico-chemical and microbial parameters. Advanced data-driven and/or mechanistic models are required to take over these data, simulate options of process control, induce automated reactions or derive recommendations for the plant operator.

Future biogas plants are envisioned to operate on a diverse feedstock spectrum that is mainly based on a wide variety of residues and complemented by promising new feedstocks and a limited proportion of crops that provide specific environmental benefits. Research is necessary to further explore and improve feedstock characteristics and to develop or optimize supply chains.

Future biogas plants need to become more efficient and more flexible with regard to input, process and output. Adapted digester technology is required which is robust and suitable to handle variable feedstock characteristics. A modular design where different components are combined and/or activated on demand supports flexibility. The development of mobile biogas plants can unlock residues that occur decentralized, seasonally and process-dependent. Progress in plant technology and process management is needed to supply biogas on demand.

Future biogas plants may become an integral part of the bioeconomy and help to produce essential chemical substances, harvest the energetic potential of residues and contribute to recycling of nutrients and organic carbon. As there is a multitude of options to use residues and to couple the production of food, bioenergy and biomaterials, favorable pathways have to be identified. Future biogas plant concepts need to explore the manifold potential linkages with the bioeconomy and to realize the most suitable ones under the individual local conditions of feedstock availability and demand for the products of anaerobic digestion.

Socioeconomic factors are likely to play a decisive role for the performance of the future agricultural biogas plants, besides techno-economic and biophysical factors. A major challenge for enterprises and researchers is the development of business models and business environments that contribute to viable and accepted production.

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