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Article

Integrated Bioenergy and Food Production—A German Survey on Structure and Developments of Anaerobic Digestion in Organic Farming Systems

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Abstract: Rising global energy needs and limited fossil fuel reserves have led to increased use of renewable energies. In Germany, this has entailed massive exploitation of agricultural biomass for biogas generation, associated with unsustainable farming practices. Organic agriculture not only reduces negative environmental impacts, organic farmers were also prime movers in anaerobic digestion (AD) in Germany. This study's aim was to identify the structure, development, and characteristics of biogas production associated with organic farming systems in order to estimate further development, as well as energetic and associated agronomic potentials. Surveys were conducted among organic farms with AD technology. 144 biogas plants could be included in the analysis. Total installed electrical capacity was 30.8 MW_{el}, accounting for only 0.8% of the total installed electrical capacity in the German biogas sector. Recently, larger plant types (>250 kW_{el}) with increased use of (also purchased) energy crops have emerged. Farmers noticed increases in yields (22% on average) and quality of cash crops in arable farming through integrated biogas production. In conclusion, although the share of AD in organic farming is relatively small it can provide various complementary socio-ecological benefits such as the enhancement of food output through digestate fertilization without additional need for land, while simultaneously reducing greenhouse gas emissions from livestock manures and soils. However, to achieve this eco-functional intensification, AD systems and their management have to be well adapted to farm size and production focus and based primarily on residue biomass.

Keywords: organic agriculture; biogas; farm survey; eco-functional intensification; agronomic productivity

1. Introduction

Growing global energy needs and increasing efforts to substitute fossil fuels have led to extensive production of agricultural biomass for purposes of renewable energy generation [1]. At the same time, energy cropping poses direct and indirect threats to the sustainability of land use systems [2,3]. Large-scale industrialized farming, in general, and intensive energy crop production, in particular, are increasingly drawing criticism from various stakeholders for their negative external effects [4–6].

Organic farming systems (OFS) alleviate the environmental burden of agricultural production by minimizing negative externalities and generating ecological benefits [7–9]. However, organic agriculture is frequently challenged for its lower productivity in terms of output per unit of land [10]. With increasing biomass demands for food, fodder, material, and energy the pressure on ecosystems and natural resources is further increasing [11], and an intensification through external input use appears inevitable to boost agricultural productivity.

Nevertheless, although organic farming faces general limitations regarding the contributions to bioenergy supply [12], approaches of integrated bioenergy and food production in organic agriculture have been discussed which might enhance both nutritional and energy output. Through integration of anaerobic digestion (AD) organic farms may contribute to the renewable energy supply without additional need for land, while simultaneously increasing food output [13]. This approach may be restricted to central European contexts and industrialized farming systems, yet it provides a contribution to overcoming the trade-offs commonly associated with agricultural biomass utilization for energetic purposes.

While the scientific literature presents sufficient evidence for multiple positive systemic effects of AD and the benefits from biogas integration in OFS have been conceptualized and described in detail [13], there is still no empirical data on AD in OFS. The aim of this study was to provide empirical data on motivations for biogas production in organic agriculture, its structure and developments, biomass input strategies, as well as impacts of digestate fertilization on organic cropping. In this paper we, therefore, present results from surveys among organic farmers in Germany who operate biogas plants. After a brief introductory section on biogas technology and organic farming systems, the survey approach and methodological challenges are described. Statements and findings are discussed with regard to energy potentials and possible effects on the sustainability of OFS and bioenergy production through AD. The paper concludes with a general outlook using the results to suggest a framework on the future role of biogas production associated with organic agriculture.

There is yet no general definition referring to an "organic biogas plant". Differences in biomass origin, the use of digestates or nutrient fluxes through biomass or digestate purchase or sales greatly vary between biogas plants as well as between organic regulations and private standards. In order to ensure readability by using a short term, in the context of this paper we define "organic biogas plant" as a biogas plant, which is associated with an agricultural farm that is certified organic according to the respective European regulation and which solely uses agricultural biomasses such as animal manures, residues or energy crops.

1.1. Biogas Systems

As a means to achieve the goal of raising the proportion of electricity from renewable energies to 21% by 2020, as promoted by the European Commission [14], many member states have passed legislation to also support bioenergy production from AD (*cf.* [15–17]). In Germany, decentralized agricultural biogas production for combined generation of heat and power (CHP) has become a major bioenergy source. In order to meet its climate protection goals, and to give incentives for more energy production from renewable resources, the German Federal Government issued the Renewable Energy Sources Act (EEG) [18]. As a result of the EEG, agricultural biogas production in Germany has been rapidly expanding. The total number of biogas plants has increased from 1050 in the year 2000 to approximately 8000 by the end of 2014, with a boost in installed electrical performance from *ca.* 100 MW_{el} to over 3700 MW_{el} [19].

Through anaerobic bacterial activity, mostly in continuously stirred tanks, agricultural biomass is decomposed, and a gaseous fuel with high methane contents (50%–70%) is produced. The gaseous fuel is utilized on-farm for internal combustion in gas engines simultaneously generating thermal and electrical energy. Electricity is fed into local grids and producers are supported through government subsidies. Heat is often considered a by-product of the process and remains underutilized, although operators have to comply with minimum heat utilization rates in order to receive the special feed-in tariffs for electrical power. Excess heat is mostly marketed independently or used on-farm (e.g., drying, heating).

Agricultural biomass used in biogas plants can be all carbonaceous organic matter directly or indirectly derived from photosynthesis. Suitable for farm biogas production are all primary and secondary agricultural biomasses containing degradable carbohydrates, such as processed and unprocessed plant materials (e.g., crop silages), crop residues (e.g., straw), animal feces, and other farm residues (e.g., from grain cleaning). After methanogenesis, the fermented effluents from the tanks are particularly rich in mineral nutrients due to the degradation of organic compounds during the process [20]. These digestates are applied to agricultural lands as fertilizer. Therefore, due to concerns of health and hygiene, sewage sludge and organic household waste are banned from farm biogas production in Germany.

In general, biogas production based on farm residues, in particular slurry and manure, is regarded to be an efficient and ecologically sustainable approach to renewable energy production [21,22]. Furthermore, there is also evidence for beneficial effects of AD technology on rural development [23]. However, high-input energy crops, instead of residues and wastes, are increasingly used in German biogas production. Anaerobic digestion of silage maize in particular has become increasingly profitable due to its exceptionally high methane yields [22]. Yet, intensive maize production is frequently associated with unsustainable farming practices and negative environmental impacts. Therefore, maize digestion bears the risk of jeopardizing benefits or outweighing positive effects of agricultural biogas systems [24].

Biogas production, in general, and intensive energy cropping, in particular, are challenged by increasing disapproval of stakeholders in society (e.g., neighbors, environmental organizations, Small Farmers' Associations). For this reason, increasing governance efforts are required from plant operators and project planners [25]. Due to its relatively large land requirements and high CO_2 avoidance costs, compared with other renewable energy options [26], maize-based co-digestion will probably not play a major role in future energy scenarios. However, it does serve as a temporary bridging technology in the transition towards a resource-efficient renewable power system [24].

1.2. Biogas Production in Organic Agriculture

Organic farming systems are low-input systems striving for closed cycles and emulating ecological processes for plant nutrition and plant protection (e.g., crop rotations). By keeping external inputs as limited as possible, organic agriculture reduces negative external effects often associated with intensive farming and is able to enhance eco-system services and ecological benefits [5,27,28]. Apart from accredited non-mineral nitrogen fertilizers, biological N_2-fixation through leguminous ley and cover crops is the sole nitrogen input in organic farming [29]. Nutrient cycling via livestock manures and the incorporation of leguminous leys may provide adequate amounts of N to meet cash crop demands. However, N-availability is a limiting factor [30] and combined with the ban of agrochemical measures of plant protection results in considerably lower yields if compared to conventional production systems [10,31].

Considering the constraints of OFS with regard to soil fertility, crop rotations, and nutrient supply, it seems implausible for organic farms to produce large quantities of energy crops for modern biogas systems without compromising its inherent sustainability principles, as formulated by the International Federation of Organic Agriculture Movements (IFOAM) [32]. Biomass available for AD in organic farming is mainly comprised of residues and waste materials. Due to the self-imposed restrictions organic residue biomass can hardly contribute significant shares of bioenergy to society's demand [12]. However, this alleged conflict between biogas and organic food production may not be completely insurmountable.

In a review of research on bioenergy and organic agriculture [33] reasons why AD may be an appropriate bioenergy technology in organic farming are discussed. Above all, nutrient management options arising from biomass fermentation and digestate fertilization are of great interest in N-limited OFS [34]. AD offers opportunities to improve nutrient cycles and may increase nitrogen accumulation especially if leguminous ley crops are used. This is due to the higher productivity of legumes when harvested and not mulched [35] as well as reduced nitrogen (N) leaching [36]. Also, gaseous nitrogen losses from mulched ley biomass and from manure in stables and storage can be reduced by AD [37]. Digestates can be applied directly to the growing crop. Furthermore, the fermentation process positively influences the availability of nutrients for plants since organic nitrogen content decreases while mineral nitrogen increases [20]. These effects and the synchronization of fertilization and plant growth contribute to more efficient nutrient cycles. Thereby, enhanced cash crop yields are possible in organic farming [38]. Further effects of AD in OFS include increased protein contents in cereals and a reduction of weed seed germinability. A detailed overview of system effects of biogas integration in OFS is given by Siegmeier *et al.* [13].

The integration of bioenergy and food production leads to possible benefits regarding farm productivity, stability, and resilience that may lead to an "eco-functional intensification" of organic systems [13]. The eco-functional intensification of organic agriculture has been claimed a strategy to manage current challenges regarding the sustainability of food and energy production. In this regard, organic farming systems are as much acknowledged for their environmental benefits as they are criticized for their low productivity and large land requirements. Through biogas integration organic farms can contribute to renewable energy supply without additional need for land while simultaneously increasing food output. At the same time, AD of livestock manures and farm residues can reduce agricultural greenhouse gas emissions (CH_4, N_2O). Therefore, through integration of AD in organic farming, enhanced sustainability of food and bioenergy production can be achieved.

Another characteristic of organic biogas production is the required compliance with organic regulations and guidelines, especially regarding biomass input and digestate use. Depending on the standards of farmers' associations (e.g., [39,40]) or the EU regulation on organic farming [41], rules for organic biogas production may differ considerably. Main differences are obvious in the use of conventionally produced biomasses, the permitted amount of nutrient import through biomass purchase, and export through biomass supply, as well as the use of biogas digestates from co-operative biogas plants operated by both organic and conventional farmers. For organic farms and biogas plants running according to the European organic standard [41] there are very few production restrictions (no restrictions on conventional biomass input, maximum import of 170 kg nitrogen (N) ha^{-1}, no restrictions of nutrient export concerning the biomass supply of conventional biogas plants). On the contrary, many organic farmers' associations restrict the import of conventional co-substrates to a maximum of 30%, moreover, admitting nutrient imports of only 40 kg N ha^{-1}. In addition, the return of digestates is permitted only if biomasses had been supplied to the biogas plant in the first place to avoid nutrient losses on the organic farm. All these regulative differences regarding organic biogas production give reasons to expect substantial variation in the actual design of organic biogas operations in practice. In particular, the additional use of external (conventional) biomasses seems to be a fundamental parameter of plant configuration which will also be dealt with below.

2. Methods

The results presented in this paper are based on questionnaire surveys among organic farmers in Germany operating biogas plants. In order to analyze the development of biogas production in organic farming, bi-annual surveys were conducted in 2007, 2009, 2011, and 2013/14. Structured questionnaires [42] were developed containing both closed and open response options, depending on the inquired subject. The questionnaires covered topics concerning structures of farm and biogas production, biomass input, use and effects of fermentation residues, as well as questions on management challenges and entrepreneurship. This paper presents results regarding the following topics:

i. Reasons for biogas production in organic agriculture
ii. Structure of organic biogas production
iii. Integrated view on farm structure and biogas production
iv. Biomass input in organic biogas plants.
v. Agronomic use and effects of fermentation residues (digestates)

Regarding topic i, farmers were asked which "considerations were important when deciding to invest into a biogas plant". Response options were "new source of income", "guaranteed revenues from electricity sales", "utilization of clover-grass", "waste heat utilization", "non-economic reasons", "nutrient management", as well as an open response option to add new items. Topic ii included questions on various technical issues of the operated biogas plants. In this paper we only consider the installed electrical capacity. In order to interrelate biogas production and the associated organic farming system, topic iii contained questions on farm type ("mixed livestock and cash crop farms", "livestock farms", "cash crop farms", "biogas farms" or "animal processing operations"), farm size, stocking density and date of conversion to organic farm management. Topic iv covered the use of biomasses produced on the farm, as well as the purchase of organic or conventional biomass, which subsequently was related to plant size and livestock density. In addition, farmers were asked whether the "profitability of my biogas plant is ensured also with the use of 100% organic biomasses". The last topic, v, addressed the use and effects of biogas digestates on the organic agricultural system. Questions covered the utilization of fermentation residues regarding amount, point in time, and respective crop, as well as whether digestates had been analyzed to determine nutrient contents. In addition, the questionnaire covered an inquiry on potential percentile yield increases of specific crops as well as positive or negative effects of digestate use on crop quality.

Organic biogas plant operators were initially identified by telephone and Internet research, *i.e.*, applying a snowball system (e.g., [43]). In order to increase the quota of organic biogas plants included in the survey, in 2011 and 2013/14 several German organic farmers' associations (*Naturland*, *Bioland*, *Biopark*, *Gäa*) were involved in distributing questionnaires among their members. Membership in private organic associations is optional. However, all organic farms are obliged to register with one of the certification bodies in order to comply with organic regulations [41]. In the 2013/14 survey nearly all certification bodies that certify and control German organic farms were asked for support in identifying and contacting additional organic biogas plant operators, three major and one smaller one finally became involved in the data inquiry. This improved approach aimed at identifying organic farms which are not a member of an organic farmers' association. It helped to improve the quota of identified plants, however, it does not overestimate the increase of plants in recent years, since newly identified biogas plants might have been managed for many years already, retrospectively changing the number of plants in the respective years.

The cooperation with organic farmers' associations and certification bodies resulted in the identification of most of the organic biogas plants in Germany. Still, our surveys do not represent a full census since participation was, of course voluntary, and contact data were not available initially due to data privacy. The distribution of questionnaires was partly carried out by appending them to farmers' associations' circulars. As a consequence, several thousand farmers received the questionnaire, even though the actual share of organic biogas farmers was assumed to be much lower. Therefore, information on questionnaire response rates is not relevant in this case. By analyzing statistical data [44] as well as expert assessments [45,46] the total number of biogas plants associated with organic farms was estimated at 160–180. Yet, the results presented here are entirely based on survey data of 144 respondents. Not all of the questionnaires were filled in completely. Also, occasionally, individual questions could not be evaluated due to imprecise or inaccurate information given by the respondent. Therefore, with each topic presented in this paper the number of analyzed data sets (n) is indicated. The goal of the study was to describe the status quo, current structure as well as possible future developments of as many organic biogas producers as possible and not to draw conclusions from a sample of organic biogas farms on the basic population. Therefore, inductive or explorative statistics were not considered in the data evaluation process in favor of an analysis employing descriptive statistics [47]. The statistical evaluation considered data from all surveys. A majority of respondents participated in several surveys, so always the most recent information entered the evaluation of the respective question. If no current data were available the latest possible data drawn from the previous surveys were considered. Even though the first survey was performed in 2007, for some of the plants the initial year of operation could be dated back to the year 1996.

3. Results

3.1. Reasons for Biogas Production in Organic Agriculture

Most important for German organic farmers in their decision to invest in AD technology were personal reasons (Figure 1). The majority of farmers (92%) stated non-economic reasons (renewable energy production, mitigation of climate change, and opposition to nuclear power) as important for them to engage in biogas production. Equally important, according to farmers' statements, were considerations of nutrient management and expected advantages of digestate fertilization (90%). 85% of the respondents stated that their on-farm need for thermal energy and a purposeful utilization of excess heat from biogas combustion was an important reason to invest in biogas production. Around 80% of the farmers stated that economic reasons (guaranteed revenues from electricity sales; new source of income) were important in their decision. The utilization of clover-grass leys was considered important only by 43% of the respondents.

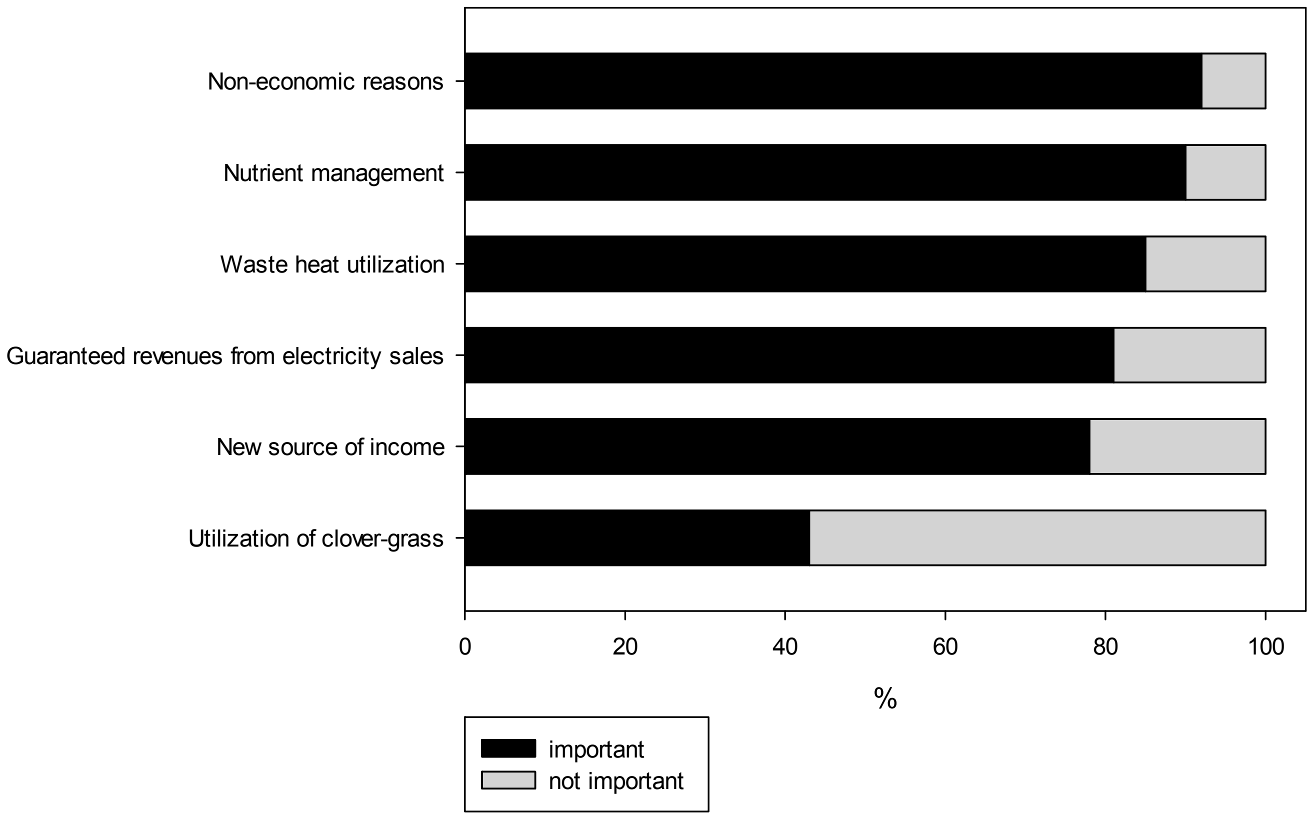

Figure 1. Reasons for the decision to invest in AD technology and their importance for organic farmers (Answers are on a 4 point Likert scale, "How important were the following reasons for your decision?", *n* = 65).

3.2. Structure of Organic Biogas Production

The number of organic biogas plants has increased from 37 in 1996 to 132 in 2014, with a maximum installed electrical capacity of 30.79 MW_{el} (Figure 2). Accordingly, the average installed electrical capacity of the regarded plants has increased from 26 kW_{el} in 1996 to 233 kW_{el} in 2014. A peak increase in newly installed organic biogas plants is identifiable in the years 2005 and 2006, following the first amendment of the German Renewable Energy Sources Act of 2004 [18], which greatly improved the economic framework conditions for biogas production in Germany in general. This increase of new plant installations in the years 2005 and 2006 corresponds to an added electrical capacity of 4.1 MW_{el} (2005) and 5.7 MW_{el} (2006), respectively.

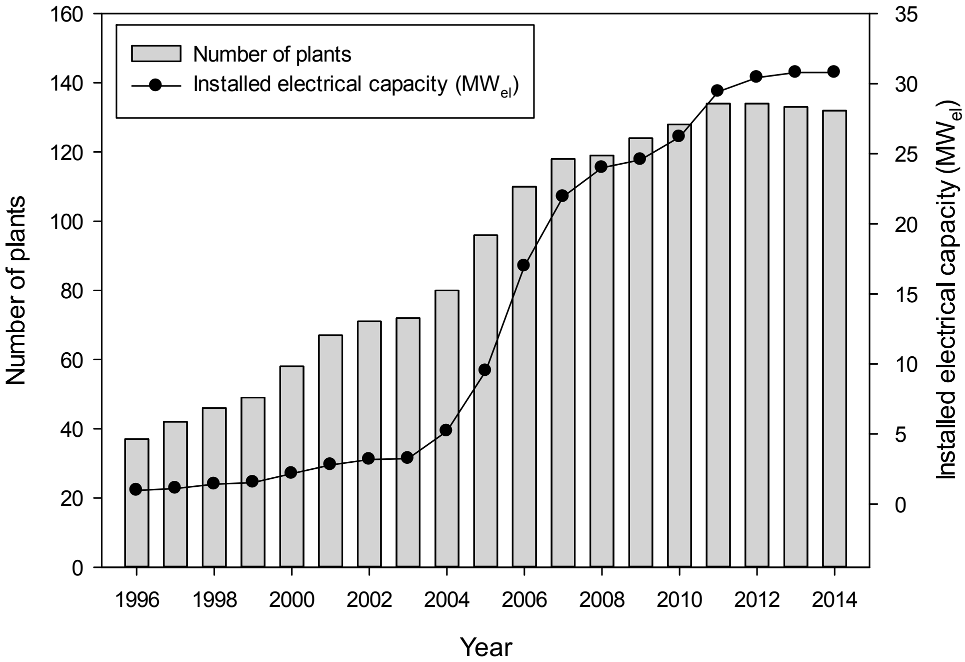

Figure 2. Number of organic biogas plants between 1996 and 2014, and their total installed electrical capacity (MW_{el}) (n = 144).

Another leap in new plant installations becomes evident after the second amendment of the German Renewable Energy Sources Act of 2009 [48], which again improved conditions for biogas production by, for example, financially supporting the use of certain biomasses such as energy maize. Based on our data sets, after 2011 there have not been any new installations of organic biogas plants. On the contrary, in 2013 and 2014 a reduction of the number of plants is noticeable. They comprise of "pioneer plants", which have been operating for 20 years and more and whose plants have reached technical obsolescence. Even though the number of organic biogas plants slightly has decreased, the installed electrical capacity has increased and has peaked in 2013 with 30.79 MW_{el}. This is especially due to the fact that some plants have expanded their installed electrical performance by adding new fermenters and CHP capacities to the existing biogas plant. As there have been biogas plants dropping out of production as well as new plants starting production, the total number (n = 144) exceeds the number of 132 organic biogas plants currently operating. Since the year 1996 (37 plants with 0.9 MW_{el} installed electrical capacity), 107 plants have gone into production (corresponding to 21.3 MW_{el}), 51 plants have increased their electrical capacity (corresponding to 8.5 MW_{el}), and 12 plants have dropped out of production (corresponding to 0.3 MW_{el}).

While, over the past fifteen years, the number of biogas plants in organic agriculture has increased, the structure of organic biogas production has also changed with regard to plant size (Figure 3). Whereas small-scale biogas plants were the predominant plant type in the late 1990s with a share of 98% of all plants, in 2014, only 35% of the organic biogas plants had CHP units of 75 kW_{el} and below. 38% of all plants were in the category between 76 and 250 kW_{el} and 27% above 250 kW_{el}.

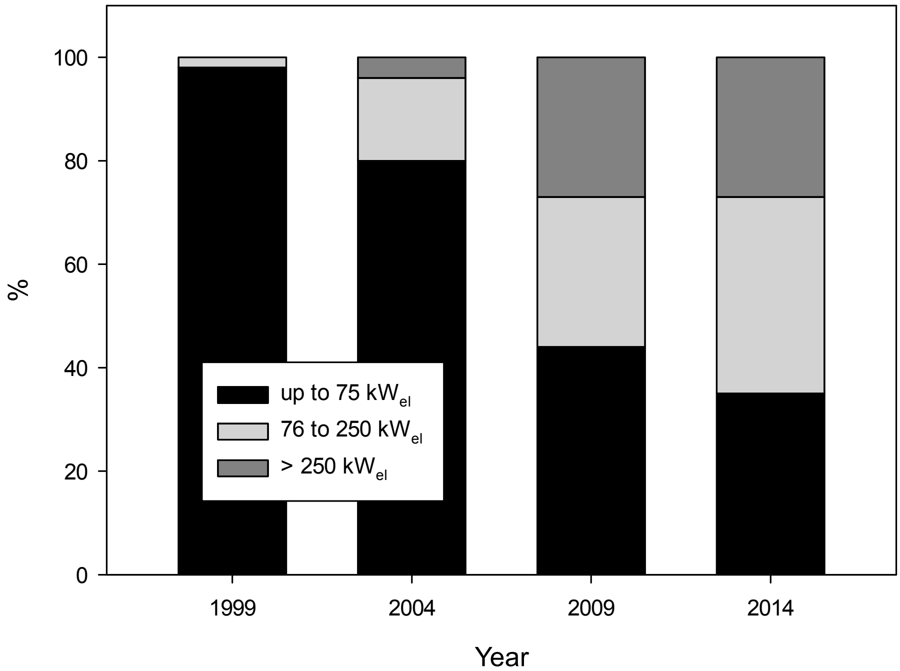

Figure 3. Share (%) of organic biogas plants grouped according to installed electrical performance (≤75 kW_{el}; 76–250 kW_{el}; >250 kW_{el}) over a period of 15 years (1999–2014) (n = 144).

The development of the biogas industry, with a shift towards large-scale biogas technology, in Germany can be attributed primarily to the legal settings between 2000 and 2014 [18,48–50]. One core element is the legally-fixed feed-in tariff, guaranteeing secure remuneration for electricity produced in the first 20 years of operation [51]. As overall biogas production (conventional and organic) greatly expanded since the year 2000, the average plant size also significantly increased from 95 kW_{el} in 2000 to 451 kW_{el} in 2013 (calculated from data by [19]). A similar development becomes apparent with regard to the structures of organic biogas production. For organic biogas plants, too, economies of scale apply, and larger-scaled plants show a tendency to be more profitable than smaller-scaled plants, as also shown by [52]. Consequently, the increase of larger-scaled biogas plants also came along with a severe change in shares of the provided “organic” electrical performance, depending on the plant size (Figure 4). While in 1999 84% of the electrical capacity was provided by plants sized 75 kW_{el} and smaller, in the year 2014 more than 60% of the installed capacity can be assigned to plants sized 250 kW_{el} and above.

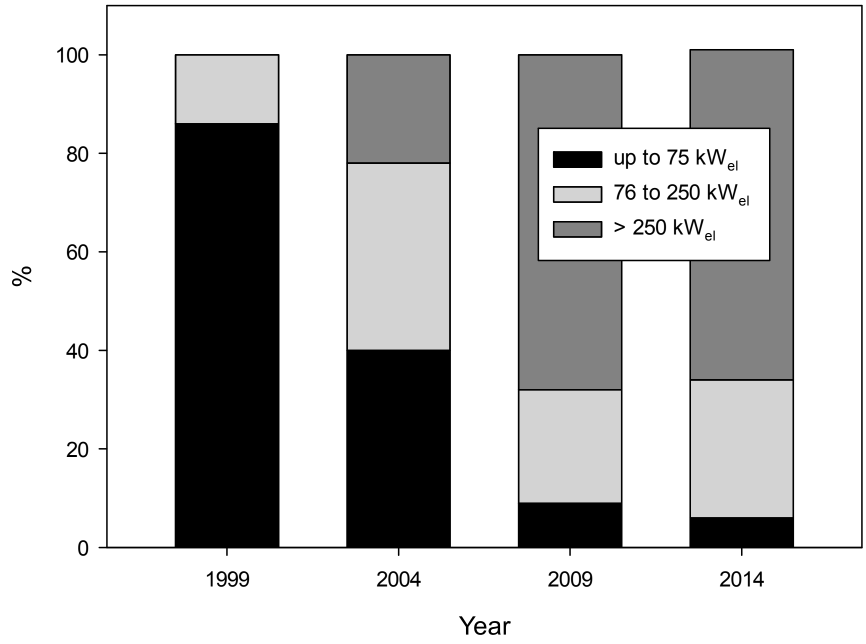

Figure 4. Share (%) of total installed electrical capacity in organic farming grouped according to the size of the CHP unit (≤75 kW_{el}; 76–250 kW_{el}; >250 kW_{el}) over a period of 15 years (1999–2014) (n = 144).

3.3. Integrated View on Farm Structure and Biogas Production

According to a self-evaluation of the respondents regarding a farm type classification (n = 103) the largest group of organic farms with biogas plants is represented by *mixed livestock and cash crop farms* (47%). About 29% of farms are *livestock farms*, with a predominance of dairy cattle and some beef, pig or poultry farming. Pure *cash crop farms* represent 16% of organic biogas producers in our survey. 5% of the respondents classified themselves as *biogas farms*, implying that more than half of the farm's annual turnover is obtained with biogas production. Around 4% classified themselves as *animal processing operations* (beef, laying hens), which display a well above average livestock density, and where a large proportion of purchase of animal feed can be assumed.

Regarding farm size, the majority of organic biogas farms are smaller than 100 hectares (ha) (Table 1). This group also shows the least average installed electrical capacity (129 kW_{el}). With growing farm size, the average installed electrical capacity tends to increase accordingly. However, the group of farms sized above 500 ha (7%) on average has smaller biogas plants (356 kW_{el}) than farms between 251 and 500 ha (486 kW_{el}). Organic biogas plants are often operated based on residue feeding such as animal manures or cover crops (*cf.* Section 3.4). Therefore, less agricultural land is occupied solely for the purpose of energy crop production than in conventional biogas production. Still, increasing plant sizes in organic biogas production also call, for example, for large manure-producing livestock units or supplementary energy cropping with extended (grass-)land requirements.

The majority (50%) of farms in the surveys have already been managed organically for 21 to 30 years (Table 2). They also represent the group with the highest installed electrical capacity (255 kW_{el}). Several of these plant operators have increased their installed electrical capacity through expansion of the plant during the past years significantly to sizes of up to 1500 kW_{el}. The second-largest group is represented by the farmers managing their farm organically for 11 to 20 years. For this group the plant size structure is similar to the largest group, with an installed electrical capacity of 241 kW_{el}. Plant size ranges from 15 to 1230 kW_{el}.

Table 1. Number, proportion and average installed electrical capacity of organic farms with biogas plant with regard to different farm size groups (*n* = 118).

Farm Size (ha)	Number of Farms (n)	Proportion of Farms (%)	Average Installed Electrical Capacity (kW_{el})
≤100	54	45.8	129
101–250	43	36.4	252
251–500	14	11.9	486
>500	7	6.9	356
Total	118	100	230

Table 2. Proportion of organic farms with biogas as well as their respective average and total installed electrical capacity depending on their length of certified organic production (*n* = 100).

Years of Certified Organic Production	Proportion of Biogas Plants (%)	Average Installed Electrical Capacity (kW_{el})	Total Installed Electrical Capacity (MW_{el})
≤10	7	101	0.71
11–20	27	241	6.74
21–30	50	255	12.74
>30	15	69	10.39
Total	100	212	21.22

The third largest group is represented by farms that operate their farms according to organic principles for more than 30 years. The majority of farmers in this group operate micro-scale biogas plants between 14 and 30 kW_{el} with one outlier of a plant size of 190 kW_{el}.

The smallest group are farmers who have been working according to organic standards for less than 10 years (7%). Their average plant size (101 kW_{el}) is the second smallest of the four groups. However, the year of converting to organic agriculture does not necessarily correspond with the year of the biogas plant installation. There is a tendency that the small plants in this group have been installed before the conversion to organic farming, whereas the two larger plants (150 and 250 kW_{el}) had been installed at the same time or after conversion to organic agriculture.

3.4. Biomass Input in Organic Biogas Plants

3.4.1. Biomass Mixtures Depending on Biogas Plant Size

On average, almost half of the input materials in organic biogas plants are animal manures (Figure 5). Together with clover-grass, silage, and other biomasses (consisting predominantly of cover crops, grain debris, and other waste materials) more than two thirds (68%) of input materials used for organic biogas production are residues (as organic farming systems rely on legume cropping for N_2-fixation, especially in stockless crop farms, clover-grass cannot be utilized in animal husbandry and is therefore classified as residue). However, biomass mixtures greatly depend on biogas plant size. Organic biogas plants with an electrical capacity of 75 kWel and below mainly rely on the use of animal manures (77%). As these plants are prevailing on *livestock* and *mixed farms*, grass silage is another important input biomass (11%). With increasing plant size the significance of animal manures decreases especially in favor of grass and clover-grass silages, rather representing the *mixed* and *cash crop farm* types.

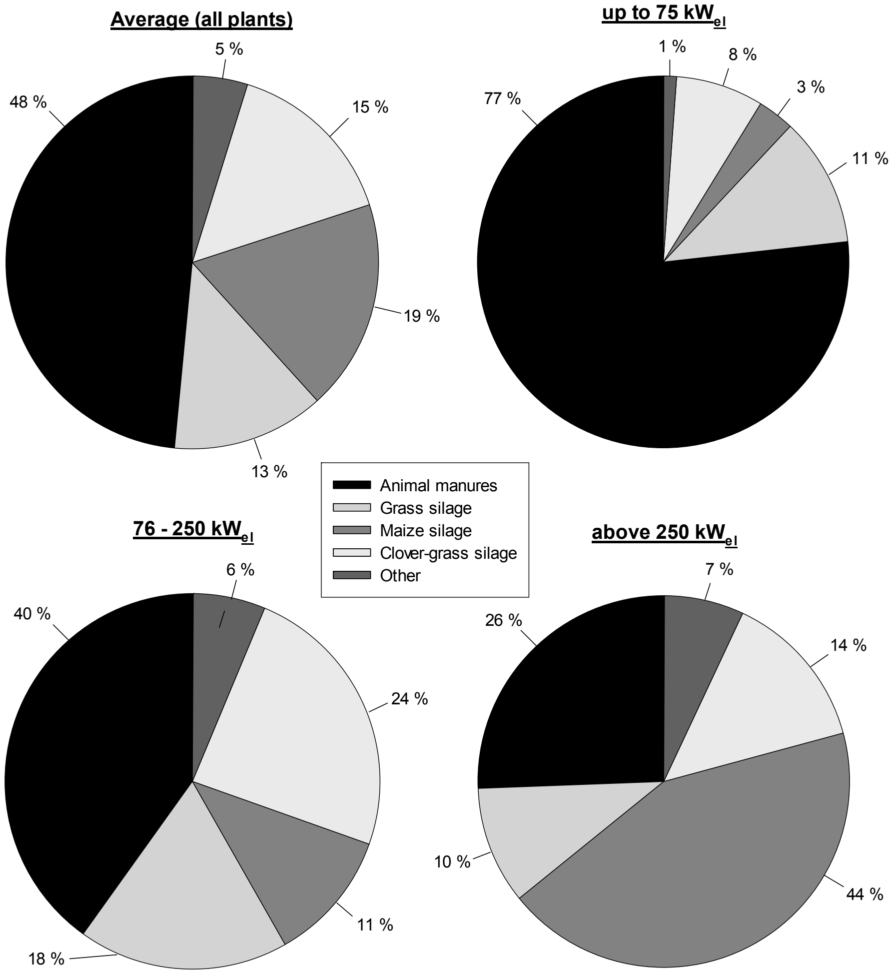

Figure 5. Average biomass input mixtures (based on fresh matter weight) for all organic biogas plants (n = 105) and plant sizes of ≤75 kWel (n = 17), 76–250 kWel (n = 73) and >250 kWel (n = 15) in 2013/14.

As the availability of large amounts of grass and clover-grass are increasingly restricted with growing plant size (usage of land area, transport distances), a strong increase of maize inputs can be observed. Unavailable organic biomasses are often substituted by conventionally grown maize (high energy yields per unit of area and above-average biogas yields) in order to meet the feeding requirements for many larger plants. As a consequence, for biogas plants with electrical capacities above 250 kWel almost half of the biomass input is maize. Given the higher gas yields of maize, compared to the other utilized biomasses, the proportion of produced biogas from maize silage accounts for more than 57%, based on standard data of gas yields (m_N^3/t FM (norm cubic meters per ton of fresh matter)) for different biomasses (*cf*. [53]). Considering the slightly lower methane content in maize-originated biogas compared to biogas from the other above-listed biomasses the average proportion of produced energy (kWh) from maize is still slightly above 56% in this group of biogas plants 250 kWel and larger.

3.4.2. Self-Sufficiency and Purchase of Organic and Conventional Biomass

As the use of, for example, conventionally produced maize is comparatively cheap in relation to organically produced energy crops, this implies severe consequences on the use of conventional input biomasses in organic biogas production. Our surveys show that the operation of 47% of plants (n = 59) is based on the additional use of conventional substrate input. Accordingly, more than half (n = 67) depends entirely on organic biomass. Yet, approximately 64% of the electrical production capacity is also generated with the help of conventional co-substrates, since those plants are typically larger than the comparative group exclusively utilizing organic inputs. Regarding average plant size, organic biogas plants operating solely based on organic biomass are considerably smaller (average of 161 kW_{el}) than plants also utilizing conventional biomass (average of 322 kW_{el}).

Organic biogas plants that exclusively rely on the supply of biomasses grown on the associated farm (*no purchase* group) are considerably smaller (average installed electrical capacity of 150 kW_{el}) than plant types which purchase either organic or conventional biomasses (Table 3). However, plant sizes range from 15 to 1000 kW_{el} in the n*o purchase* group, so apparently large scale organic biogas plants can be supplied with 100% on-farm biomasses, too. Biogas plants in the *organic purchase* group are slightly larger (210 kW_{el} on average). Both of these groups, solely based on organic input materials, have high ratios of farm size (ha) and livestock density (livestock unit, LU) in relation to the installed electrical capacity (ha kW_{el}^{-1}; LU kW_{el}^{-1}).

Table 3. Average installed electrical capacity, farm size and livestock density depending on feeding strategies based on *no biomass purchase*, *organic* and/or *conventional biomass purchase.*

Type of Biogas Plant According to Biomass Purchase	Average Installed Electrical Capacity (kW_{el}) (n = 127)	Average Farm Size (ha kW_{el}^{-1}) (n = 121)	Average Livestock Density (LU kW_{el}^{-1}) (n = 117)
No purchase	150	2.1	2.3
Organic purchase	210	2.3	1.5
Conventional purchase	241	1.2	1.0
Organic and conventional purchase	418	0.6	0.3

Organic biogas plants relying on the additional input of conventional biomasses (*conventional purchase* group) again are somewhat larger on average than plants using exclusively organic input materials (241 kW_{el}). Plants that are run on significant shares of external input biomasses (*organic and conventional biomasses purchase* group) are characterized by very high average installed electrical capacities (418 kW_{el}).

3.5. Agronomic Use and Effects of Fermentation Residues (Digestate)

Biogas fermentation residues (digestates) are a valuable organic fertilizer displaying high contents of easily accessible nitrogen, being one of the most important nutrients for plant growth. As the availability of nitrogen is restricted in organic agriculture [30], the sensible use of digestates can help to improve nitrogen efficiency on organic farms, leading to yield increases and higher product qualities [38,54,55].

Especially for stockless farms, the availability of a mobile fertilizer can significantly improve nutrient efficiency and productivity [13].

Farmers were asked to state their observations on yield increases through digestate fertilization. About one sixth of farmers noticed increases of crop yields of up to 10%. Half of the interviewed report yield increases between 10% and 20%, and still 35% noticed even higher yield increases above 20% (of which 13% noticed yield increases of more than 30%). Digestates are used almost exclusively in arable crops. Stable crop-specific yield increases between 20% and 25% were reported for cereals, root crops/maize (the term “root crop” in this context is used for crops where mechanical cultivation techniques, such as e.g., harrowing are applied repetitively in order to ensure weed control and nutrient mobilization. Due to intensive mechanical crop cultivation during the growing season, in organic agriculture, maize is considered a root crop, too) and grassland. Very high yield increases were observed for oil crops. However, experience with these crops is relatively small due to the very small scale of cultivation of sunflower or rapeseed in German organic agriculture. Average overall yield increases for agricultural crops as stated by the respondents are at 22%.

In addition, organic biogas farmers give account of changing crop qualities through biogas digestate fertilization. Main effect is observed in cereal (esp. wheat) production, where increased crude protein contents as well as higher gluten contents are occurring. These enhanced baking properties pay off in higher sales prices for cereals and therefore an increased overall farm income. Moreover, in grassland fertilization increasing proportions of desired grass species with higher fodder values are observed through digestate application, leading to higher energy contents of animal feedstuffs.

On the other hand, some negative effects of digestate application were reported such as the higher potential of chemical burns on plant leaves as well as the higher volatility of nitrogen compounds, demanding a more complex fertilization management. Further topics named were a higher weed pressure, a higher risk for erosion and a less perpetual fertilizing effect during the growing season.

4. Discussion

4.1. Energy Potential of Organic Biogas

The number of organic biogas plants, as well their electrical capacity, have increased tremendously (*cf.* Section 3.2). This trend is reflected by the rapid development of the entire biogas sector in Germany during the past 20 years (*cf.* Section 1.1, [19]), strongly linked to the public promotion of renewable energy sources based on the German Renewable Energy Act. This applies to biogas production on organic farms, too, only on a much smaller scale. In 2014, around 26% (161 TWh) of the total gross electricity production in Germany was provided by renewable energy carriers, from which approximately 49 TWh were generated by the energetic use of biomasses (solid, liquid, gaseous bioenergy carriers) [55]. As the proportion of electricity from biogas accounts for 18% of the total energy provision by renewable energy sources (corresponding to about 29 TWh, calculated from [55]), the above presented installed electrical capacity of organic biogas plants (30.79 MW_{el}) contributes only marginally to the overall mix of renewable energy sources. Information on plant utilization rates were scarcely given, however, our survey data indicate an average annual plant utilization well below the generally least targeted 8000 ha^{-1}. This can be attributed to the use of biomass high in ligno-cellulose contents, such as grass or clover-grass silages, leading to increased maintenance demands of stirring equipment and pumping devices. Also, due to the more diverse organic biomass input mix the biological processes of biogas generation are less stable than in mainly maize-based feeding strategies. Assuming an annual plant utilization of 7000 ha^{-1}, the installed electrical capacity of organic biogas plants would account for a provision of "organic" electricity of approximately 0.22 TWh or 0.7% of the total electricity provided by biogas plants in Germany. Relating the total installed electrical capacity of all biogas plants in Germany (3543 MW_{el}; [19]) to the currently installed electrical capacity of organic biogas plants (30.79 MW_{el}), the proportion of "organic" electrical capacity is at 0.8% and corresponds fairly well with the calculated provision of "organic" electricity.

According to Grieb & Zerger [56] the theoretical biological energy potential for organic biogas production is assumed to be much higher (about 10 TWh per year). These calculations include all biomasses usable in organic production (15% from organic animal husbandry, 64% from organic plant residues) as well as biomass from landscape preservation (21%) which is not certified organic but not treated with any substances or farming practices prohibited according to organic production standards. However, not all of the above-stated biomass is actually available, due to technical and economic restrictions. In addition, the growth rates of organic agriculture have slightly declined over the past seven years [57], and some organic farmers are even reconverting to conventional agriculture, also possibly leading to reduced land area potentials for organic biogas production [58,59]. Still, based on the above-cited theoretical biological energy potential for organic biogas production, if an electrical efficiency rate of 37%, a thermal efficiency rate of 48%, and a share of externally used heat of 50% is assumed, these biomass potentials would account for the provision of 3.7 TWh electrical and 2.4 TWh thermal energy after all.

4.2. Sustainability of Biogas Production Associated with Organic Farming Systems

4.2.1. Avoidance of Land Use Competition between Food and Energy through Residue Utilization and Increased Agronomic Productivity

The current share and potentials for energy provision based on organic biogas production are relatively low (*cf.* Section 4.1). However, in order to be able to evaluate organic biogas production holistically, the additional benefits should be considered. A major benefit is the joined provision of sustainably-produced bioenergy and the increasing productivity of the associated organic farming system at the same time. With rising global energy needs and the finiteness of fossil energy carriers [60,61], as well as an increasing world population, the precedence of food versus energy production is sincerely discussed, addressing the problems of regional land use competition as well as indirect land use changes (ILUC) [62].

By mainly using residues for fermentation purposes in organic biogas production land use competition between food and energy utilization is mostly avoided. On the contrary, the utilization of residual materials for biogas generation does not contradict but even complements food production. Through direct and indirect effects of anaerobic digestion enhanced crop yields can be achieved. Of course, farmers' statements in the surveys about enhanced yields and qualities are not verifiable and the survey did not gather information on whether they rely on personal estimations or on actual measurements. However, both research based on field trials [35,38,60,61,63,64], as well as model calculations [65], indicate similar findings on occurrence and range of yield effects and the quality enhancement of harvests.

The survey data do not clearly indicate the explicit cause(s) of yield increases. Therefore, it remains uncertain whether they are induced by increased proportions of NH_4 in the digestates, and therefore enhanced plant availability, or by an increased total amount of nutrients through biomass purchase. From 99 farmers who reported yield increases, 41% purchased biomass, 17% did not (the missing 41% did not give information on biomass purchase). This could indicate the effect of additional nutrient import. However, when closely analyzing the groups of plant operators that noticed low (≤10%) and also very high (>30%) yield increases, the proportion of biogas plants purchasing external biomass is nearly equally distributed with the ones that do not. In addition, farms operating according to the European organic standard (permitting high nitrogen imports of 170 kg N ha^{-1}) do not show higher yield increase rates than members of German organic farmers' associations (nitrogen import limited to 40 kg N ha^{-1}). The survey data also revealed that farmers often times swap biomass (esp. clover-grass) in exchange for digestate without any nutrient import. Therefore, yield effects are most likely triggered by improved digestate composition and a better spatio-temporal availability as well as increased N_2-fixation rates when clover-grass is harvested and not mulched. In conclusion, both the effects of fertilizer composition and nutrient availability, as well as the additional nutrient import, might be responsible for yield increases. Even more importantly, individual farm factors such as soil composition, climatic conditions and, in particular, nutrient management (direct incorporation of digestates—rich in volatile N compounds—into the soil, close observation of suitable weather conditions) most likely have a crucial impact on yield effects. Nevertheless, by purchasing conventionally produced biomass, organic farming systems stimulate the use of mineral fertilizers. Especially regarding nitrogen, this contradicts one of the main principles of organic agriculture, which seeks to be preferably independent from purchased nitrogen sources, yet permitting the purchase of non-mineral N fertilizers. However, according to the survey data, stabilized or even enhanced yields in organic farming systems with integrated biogas production can hardly be solely reduced to the import of additional nutrients by biomass purchase but are a result of many different aspects as described in this chapter.

Both the above listed results as well as findings in the literature indicate that an integrated biogas approach can achieve an increased (organic) food supply through a more efficient nutrient management and therefore sustain or even enhance productivity (e.g., [13,35,59,62]) while at the same time securing the provision of ecosystem services. Systemic effects enhancing performance particularly include improved nutrient efficiency through a better spatiotemporal allocation of biogas digestates. This is accompanied by an enhanced plant availability of nitrogen (N) from biogas fermentation residues. The effects can be increased yields and product quality (e.g., grain protein content) as well as changes in crop rotation towards more N-demanding crops, resulting in a better market performance of the whole crop rotation and therefore increased income of the entire OFS.

Using clover-grass for biogas production, especially in stockless farming systems instead of mulching, leads to increased N_2 fixation of legumes by up to 20% and to reduced N_2O emissions harmful to the climate [35]. In addition, positive phytosanitary effects through weed seed reduction during fermentation [66] or enhanced plant health through more diversified crop rotations are possible outcomes. Taking these additional benefits into account, the integration of biogas in organic farms can help to restore economic sustainability of the whole farming system through an enhanced productivity of food production, assisting to the goal of an "eco-functional intensification" in organic agriculture, as well as contribute to the satisfaction of increasing global food demands.

On the other hand, potentials for yield increases might also be threatened by the use of fermentation residues (*cf*. Section 3.5 and e.g., [38]). In contrast to findings from laboratory batch trials that strongly reduced germinable weed seeds [67,68], farmers noticed a higher weed pressure, which might be induced by a higher nitrogen availability, resulting in the competition for factors important for crop growth (water, light). Other observed aspects such as a higher risk for erosion and a less perpetual fertilizing effect can be associated with the lower structure and dry matter contents of digestates compared to unfermented slurry, resulting in lower abilities to avoid erosive incidents and a lower proportion of more strongly embedded and therefore long-term available nitrogen. Four premises for an "eco-functional intensification" of organic farming systems through AD integration have been discussed in the literature [13] concerning (i) the general AD system design; (ii) the cropping system; (iii) management requirements; and (iv) the technical configurations of biogas plants. With regard to the general design, it is essential that biogas production is adapted to a farm's size and production focus. A farm's potential residue and waste biomass should be the basis for careful planning of the capacity and design of a biogas plant in order to achieve efficiency increases through AD integration, without compromising food production of the organic system [13]. From the survey data it could be shown that many of the larger biogas plants are not operated on the basis of waste and residue biomass alone. Rather they rely on purchased energy maize which is directly competing with food cropping.

4.2.2. Realization of Adapted Biogas Systems

Model calculations have shown that—in order to meet the input requirements of biogas plants—an agronomically-sustainable integration of biogas production into typical organic crop rotations, according to organic agronomic principles (e.g., two year cultivation clover-grass within the crop rotation), requires farm sizes between 340 ha (75 kW_{el}) and 1500 ha (500 kW_{el}) for livestock farms with a mainly manure-based biogas plant feeding, and between 120 ha (75 kW_{el}) and 815 ha (500 kW_{el}) for cash crop farms with a mainly plant-based input strategy [66]. Although, the size of organic biogas farms with an average of 219 ha is well above the average size of organic farms (45 ha) in Germany in 2014 [58], it is hardly enough land to provide sufficient quantities of ley biomass and animal manures for the operation of large biogas plants (>250 kW_{el}). For instance, where the ratio between farm size and livestock density in relation to the installed electrical capacity (Table 3) is around 1 (*conventional biomass purchase* group), or even below 1 (*organic and conventional biomass purchase* group), it is impossible to supply biogas plants exclusively with own farm biomasses. Here large amounts of additional inputs need to be purchased and transported to the plant. In terms of sustainable biogas production implying low biomass transport distances and the use of organically produced biomasses, those biogas plants can be regarded as poorly adapted to the farm's structures, *i.e.*, oversized. On the other hand, farm size ratios of 2.1 and 2.3 ha kW_{el}^{-1}, respectively (*no purchase* group), as well as livestock densities of 2.3 and 1.5 LU kW_{el}^{-1}, respectively (*organic purchase* group), guarantee an almost complete or even total on-farm supply of biomass for fermentation. These biogas plants can be qualified as well adapted to the farm structures, ensuring short transport distances for biomasses and therefore lower energy needs and CO_2 emissions.

4.2.3. Strategies of Biomass Use

One of the most controversially discussed aspects in organically produced biogas, touching on the premises of sustainable biogas production, is the additional use of conventionally originated co-substrates. The promotion of certain energy crops under the German EEG law has led to a significant increase, especially in large maize monoculture cropping practices, as maize assures comparatively high energy yields per hectare with high biogas yields during fermentation at the same time. Reasons for the increased use of conventional biomass in organic biogas production can be seen in (i) bad planning of biogas plants that are too large for the exclusive use of own, on-farm inputs or (ii) deliberate planning in order to enhance methane and therefore economic yields by using supplementary low-cost substrates [16]. However, the intensified use of conventionally produced biomasses contradicts the organic idea of a preferably closed farm cycle and may negatively influence customer perception concerning organic biogas production and organic food products. In addition, it threatens the credibility of organic agriculture in general and causes disputes among organic farmers. While the practice of using a maximum of 30% conventional inputs is still permitted, a number of organic farmers' associations in Germany will ban the use of conventional biomass by the year 2020 [39,40]. For already existing organic biogas plants, this shift to operating on 100% organic biomasses might become a severe economic challenge, since organic biomass is more costly than conventional. The surveys of 2011 and 2013/14 covered the question, whether the "*profitability of my biogas plant is ensured also with the use of 100% organic biomasses*". Almost two thirds answered with *definitely not*, *rather not* or *unsure* (*definitely not*: 30%; *rather not*: 12%; *unsure*: 15%), whereas only less than half of the plant operators answered *rather yes* or *definitely yes* (*rather yes*: 11%; *definitely yes*: 32%). Reasons for this predominantly pessimistic view on economic sustainability with the use of 100% organic biomass input can be summarized (i) in an overall low biomass availability due to increasing transport distances, caused by the comparatively small share of organic farms and their scattered location and (ii) in the relative excellence of cash crop production, compared to energy crop production, since organically produced cash crops generate a premium price on the organic market, whereas there are no additional remuneration incentives in biogas production for the use of organically-produced energy crops. Hence, on the one hand the demand of 100% organic input biomasses might induce drop-outs of several organic biogas farms from organic farmers' associations, turning to minimum standard agricultural practices according to the EC regulation or reconverting to conventional agriculture entirely. On the other hand, this will lead to a further "greening" of organic biogas with the realization of heightened sustainability standards.

5. Conclusions and Outlook

The aim of the analysis of current structures and development of organic biogas production was to better understand the driving forces, constraints, and future role of a sustainable energy production through generation of electricity from biogas. As biogas was also developed on, and integrated into, organic farms in order to attain the goal of a preferably independent farming system by a few dedicated pioneers, today, despite of its rapid growth rates it still plays a rather subordinate role regarding the share of renewable energy provision. With regard to the scarcity of land resources worldwide, it seems improbable that organic biogas production will provide a substantial contribution to the world's energy needs based on renewable energy resources. The characteristics of organic energy crop production with lower yields at higher costs and land area requirements are incompatible with a vast expansion of organic energy cropping. In addition, an increased utilization of crops solely produced for energy production would lead to an aggravated competition for land resources, not only locally but worldwide (ILUC), implying large transport distances and increased risks for the degradation of soil and biodiversity. Moreover, the credibility of organic farming systems both for producers and consumers of organic products would be vigorously undermined by this kind of bioenergy production.

However, even though energy production from biomass will not solely be able to replace fossil fuels, with the aim to reach independence from fossil or nuclear energy resources, biogas production may well be, and remain, an important pillar as part of an energy mix comprising solar, wind, biomass, and hydro power. Especially if Central European conditions are considered, the only reasonable practice for organic biogas production seems a holistic, integrated approach, considering a balanced focus on both food production and contribution to increasing energy demands. This includes biogas concepts adapted to the associated farming system (small to medium sized biogas plants, including inter-farm co-operations) primarily based on residue feeding and a quite moderate and ecologically sound cultivation of energy crops. This approach ensures a sustainable provision of energy while at the same time enhancing agronomic efficiency by increasing food output through "eco-functional intensification".

As organic biogas production is more costly due to its higher environmental standards, this will also require adjustments in the public promotion of sustainable bioenergy production systems, both from governmental promotion and from the consumer's willingness to pay higher prices for eco-friendly energy.

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Author Contributions

Benjamin Blumenstein and Torsten Siegmeier have designed and conducted the farm surveys 2011 and 2013/14. They have jointly thought of the structure of this paper and have written the text. Carsten Bruckhaus assisted Benjamin Blumenstein and Torsten Siegmeier in the survey of 2013/14 and helped with data analysis 2013/14. Victor Anspach has designed and conducted the surveys 2007 and 2009. Victor Anspach and Detlev Möller contributed to the discussion and conclusions of this article.

Conflicts of Interest

The authors declare no conflict of interest.

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