Middle East Journal of Agriculture Research
Volume: 10 | Issue: 03| July – Sept.| 2021

EISSN: 2706-7955 ISSN: 2077-4605
DOI: 10.36632/mejar/2021.10.3.57
Journal homepage: www.curresweb.com
Pages: 842-851

Comparison between Agricultural Biogas Systems in Relation to Greenhouse Gas Emissions

Mona Maze[1], Omar Hijazi[2], Bianca Zerhusen[3] and Mathias Effenberger[3]

[1]Agricultural Research Center, El-Gamaa Street 9, 12613, Giza, Egypt.
E-mail: mona _maze @ yahoo .de
[2]Chair of Wood Science, Technical University of Munich, 85354 Freising, Germany.
E-mail: hijazi@hfm.tum.de
[3]Bavarian State Research Center for Agriculture, Institute for Agricultural Engineering and Animal Husbandry, Vöttinger Strasse 36, 85354 Freising, Germany

Received: 24 June 2021 **Accepted:** 15 July 2021 **Published:** 30 July 2021

ABSTRACT

The utilization of the different renewable energy sources in Germany has expanded in the last twenty years, where the renewable share in gross power consumption has gone from 5% to 35%. The construction of biogas plants has increased almost 10 times since 2000 to 2018 that the installed electrical power reached close to 5 GW. This paper presents an evaluation of the Life Cycle Assessment (LCA) of four biogas plants in different soil climate regions in Bavaria. The article discusses the different utilization, management and share of feedstocks (manure and energy crops) in the biogas plants and their influence on the electricity generation and the GHG emissions, whereas the biogas plant with higher share of energy crops and maize silage, in particular, showed higher GHG emissions and generated more electricity than the biogas plants with higher share of manure. The produced GHG emissions as a result of the electricity and heat supply from the biogas plants have been compared with the emissions that are created from the German grid mix and the different fossil fuels for generating electricity and heat. The results could be further employed to select the best agricultural biogas system with minimum GHG emissions in Egypt.

Keywords: Biogas plants, Biogas system, global warming, Green House Gas emissions (GHG), Life Cycle Assessment (LCA), environmental impacts

1. Introduction

Due to uncurbed emissions of greenhouse gases (GHGs), the world is proceeding on a pathway of global warming to an extent that poses high risks to humanity with respect to both the rapidity and the potential irreversibility of the changes in global ecosystems. Energy production from fossil fuels has been the main driver of rising emissions of the long-lived GHG carbon dioxide and of a substantial share of the short-lived GHG methane (Friedlingstein *et al.,* 2019; Ripple *et al.,* 2020). In order to limit the expected peak of warming and minimize the above-mentioned risks, it is therefore not only necessary and extremely urgent to phase-out the use of fossil fuels, but likely unavoidable to also employ measures for active extraction of carbon dioxide from the atmosphere (Hansen *et al.,* 2017).

The only viable option at hand to replace fossil energy carriers from their domination of global energy supply appears to be the utilization of a wide range of so-called renewable energy sources (RES), in conjunction with fundamental changes of energy system infrastructure and control (Moomaw *et al.,* 2011), where increasing the capacity of power generation from variable RES has already caused major changes in electricity markets and prices (Lauven *et al.,* 2019). Biogas production by means of anaerobic digestion (AD) is one of the most proven and versatile RES technologies (Lamnatou *et al.,* 2019). In Germany, the biogas plants increased from 850 installations with a total electrical capacity of about 50 MW in 1999 to 9,444 installations with close to 5,000 MW in 2018 (Fachverband Biogas,

Corresponding Author: Omar Hijazi, Chair of Wood Science, Technical University of Munich, 85354 Freising, Germany. E-mail: hijazi@hfm.tum.de

2019). Most of the biogas is utilized for combined heat-and-power-production and, although a considerable fraction of the heat output remains unexploited, German biogas plants constitute 50% of the total heat market from biogas in the EU (Scarlat *et al.,* 2018). The biogas plants generate digestate as a byproduct, which is used as a fertilizer that, in comparison to raw liquid animal manure, is more accessible to plants and strongly reduced in pathogens (Russo and von Blottnitz, 2017).

In terms of calorific content, the dominating feedstock for biogas production in Germany is energy crops, followed by animal excrements and municipal bio-waste (Daniel-Gromke *et al.,* 2018). While the utilization of energy crops results in relatively favorable biogas yields, it generates considerable burdens in terms of high production cost and environmental impacts, particularly GHG emissions and competition for agricultural land (Kränzlein, 2008; Britz & Delzeit, 2013). In order to evaluate the environmental impacts that are related to the production of biogas by means of AD, Life Cycle Assessment (LCA) has been widely adopted, offering useful information about the environmental profile of these systems (Bacenetti *et al.,* 2016; Hijazi *et al.,* 2016). Whether the purpose of AD is predominantly waste management or energy production, will significantly affect the outcomes of LCA for biogas systems (Häkkinen *et al.,* 2013).

The paper objective is to evaluate GHG emissions of different biogas plants, which have been fed with different feedstock (manure and energy crops). The studied farms are located in different locations in Bavaria, Germany, at three different soil climatic regions (BKR). The LCA was calculated using the software GaBi 6.0 (thinkstep AG, Germany).

2. Materials and Methods

The LCA study was conducted according to ISO 14040 (2006), ISO 14044 (2006). The utilized life cycle impact assessment (LCIA) level is the midpoint impact category indicator of the environmental mechanism, which translates impacts into environmental themes such as climate change, acidification and human toxicity.

2.1. Goal and scope of the study

The goal of this study was to present the specific impacts on global warming / greenhouse gas emissions of producing and utilizing biogas from agricultural input materials as an energy source. Therefore, one electrical kilowatt hour (kWh) of power fed into the grid was used as functional unit. A biogas chain with feedstocks from agriculture consists of numerous conversion steps and is in part an open system. For the purpose of LCA, this system was divided into the four stages of feedstock supply, biogas production, use of digestate, and biogas utilization, as illustrated in Figure 1.

Four biogas plants on four farms in Bavaria were performed at this study. The studied sites consisted of one organic farm (site 2) with a total area 290 ha and joined with a cattle fattening farm (Table 1). The other farms 1, 3 and 4 are conventional farms with total areas 256, 106 and 38 ha, respectively. Farms 1, 2 and 3 were connected directly to dairy cattle, poultry and pig fattening farms, respectively. Farm 4 was not connected to any animal farm, therefore cattle manure was brought as an input material. The deliberated farms are located in three different soil climate regions (Boden-Klima-Räume 'BKR'), which are 113, 115 and 117 (Figure 2). The BKR represents the spatial classification of Germany, according to the soil-climatic areas that is tailored to the agricultural operations with respect to the municipal boundaries (Roßberg *et al.,* 2007), where the soil type at the four sites ranged from sandy loam to loam.

The variability of GHG emissions from the studied biogas systems is examined in order to illustrate the effect of different input materials on the resulted GHG emissions. Input materials for biogas production in these farms were animal manure (AM), maize silage, grass silage, and other energy crops / renewable raw materials (RRM; Figure 3). In all cases, the biogas was utilized for combined heat-and-power production (CHP) on site. The installed electrical capacity of the CHP units, P_{el} in the four case studies ranged from 100 kW for Farm 4, over 250 kW for Farms 2 and 3, to 650 kW for Farm 1 (Tale 1). Different shares of the generated electricity from the studied biogas plants have been assigned for the CHP operating. The generated heat from farm 2 has been used at a business scale, while the remaining sites were used for heating the surrounding houses.

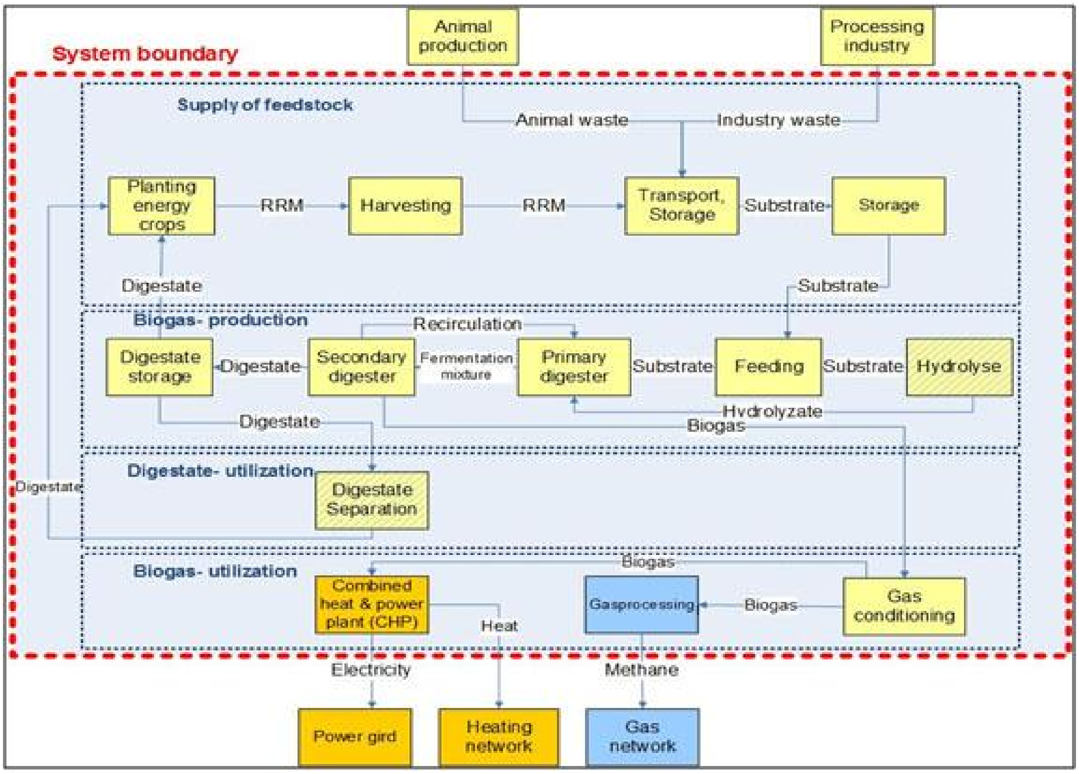

Fig. 1: System boundary and structure of biogas energy systems for LCA (RRM: renewable raw materials).

Table 1: Characterization of the farms and their biogas plants.

ID	Feedstock*	Nominal electrical power output of CHP unit, kW	Proportionate electricity demand of biogas plant§, %	Proportional heat sales$, %	Heat utilization	Soil type	BKR	Total farm area (ha)	Animal husbandry	Farm type
1	MS, GS, RT, DCM, CCM, WW	650	7.7	81	Hospital, private houses	sandy loam	115 Tertiär-hügelland Donau-Süd	256	Dairy cattle, poultry	Conventional
2	CGS, SCM, GS, MS, TS, RS, BG	250	10.2	56	District heating network (private & business)	sandy loam, loam	115 Tertiär-hügelland Donau-Süd	290	Cattle fattening	Organic
3	MS, CM, PM, RT, WW, GS	250	6.2	57	Hospital, private houses	sandy loam	113 Nordwestbayern–Franken	106	Pig fattening	Conventional
4	GS, CM, MS	100	17.6	92	Private houses	Loam	117 Moränen-Hügelland und Voralpenland	38	None	Conventional

*) CCM: Corn-Cob-Mix, CG: Clover grass, CM: Cattle manure, SCM: Solid cattle manure, DCM: Dairy cattle manure, RT: Rye-Triticale, WW: Winter wheat, CGS: Clover grass silage, GS: Grass silage, MS: Maize silage, PM: Pig manure, TS: Triticale silage, RS: Rye silage; §) With respect to electricity output; $) With respect to surplus heat after satisfying digester heat demand.

Middle East J. Agric. Res., 10(3): 842-851, 2021
EISSN: 2706-7955 ISSN: 2077-4605 *DOI: 10.36632/mejar/2021.10.3.57*

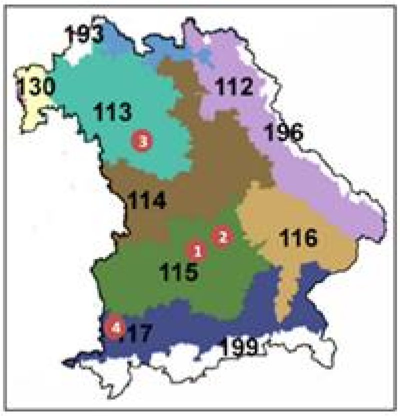

Fig. 2: The location of the studied sites in Bavaria and its soil climate regions (BKR).

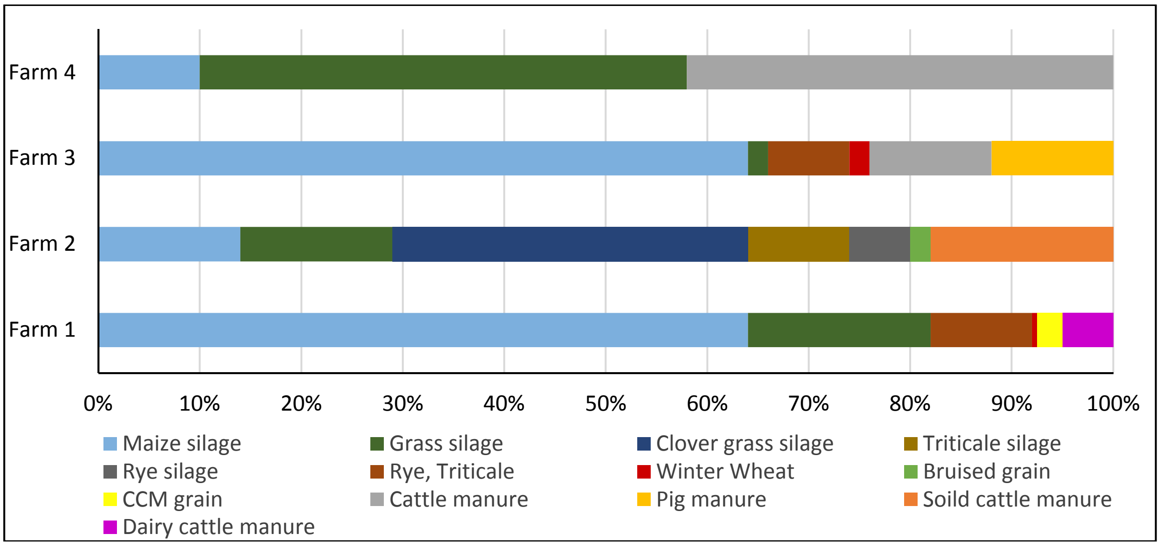

Fig. 3: Characterization of the mix of input materials for biogas production in the four case studies; percentages refer to the share of different materials in total fresh matter (FM) input mass over the period of one year.

2.2. Life-cycle inventory (LCI) data

GaBi 6.0 (source GaBi, 2013), software and its enhanced database, was used to calculate related environmental impacts on the biogas production and specific GHG emissions of electricity and heat generation from biogas, we followed the standardized methodology of life cycle assessment (LCA), using the GaBi® 6.0 tool (thinkstep AG, Germany) and ecoinvent 2.2 database. The LCI for the biogas systems was compiled from primary data collected from the farms four times as replicates, supplemented by generic data from literature/databases. The calculated emissions covered the following system components

- Machinery and equipment: stirring devices, pumps and heating appliances;
- Feedstock supply: provision of RRM from cropland and grassland (whereas animal manure production was treated outside the system boundary), feeding the substrates into the biogas plant, mixing and wheeled loader process;
- Construction of the AD plant and the silo;
- Supply of electricity for operating the AD plant; and
- Combined heat-and-power plant.

For characterizing the impact on global warming, the main GHGs carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were quantified, applying the global warming potential (GWP) for a 100-year time horizon of 298 for N_2O and of 25 for biogenic CH_4 according to IPCC (2007). The emissions from feedstock supply were calculated using the 'GHG Calculator Biogas' (Maze *et al.,* 2017; Zerhusen *et al.,* 2019). For life cycle impact assessment, the CML 2001 method as implemented in GaBi® 6.0 was applied with 1-year balance, 100 years gas observation in the atmosphere and standardized effect according to the dwell time.

2.3. Environmental impacts

Several thermodynamic and economic approaches are available to perform allocation of GHG emissions. For this study, the exegetic allocation method was chosen, whereby exergy is defined as the part of a system's energy content which can be converted into mechanical work (Nuorkivi, 2010). While electricity is 100 % exergy, heat is only partially convertible into mechanical work. If exergetic allocation is performed, electricity will therefore bear the main part of the system's GHG emissions whereas the emission share allocated to heat will remain relatively small (see Equations 1 to 3, after Wolf *et al.,* 2016).

$$E_Q = Q \cdot \left(1 - \frac{T_U}{T_Q}\right) \quad \textit{(Eq.1)}$$

$$AF_{\text{Power}} = \frac{W_{el}}{W_{el} + \dot{E}_Q} \quad \textit{(Eq.2)}$$

$$AF_{\text{Heat}} = 1 - AF_{\text{Power}} \quad \textit{(Eq.3);}$$

AF_{Power}	=	Allocation factor for power, 1
AF_{Heat}	=	Allocation factor for heat, 1
W_{el}	=	Generated electrical power, MJ
E_Q	=	Exergy of heat, MJ
Q	=	Lower heating value of biogas, MJ
T_U	=	Ambient temperature, K (Reference temperature = 288 K)
T_Q	=	Temperature of heat output, K (Reference temperature = 344 K)

2.4. Statistical analysis

Data obtained from the four sites was combined in a single analysis. Analysis of variance and Duncan's Multiple range test ate 0.05 level means separation test using MSTST (1985). Software C was used to compare the collected data.

3. Results

The biogas plants analysis focused on comparing GHG emissions from the different case studies, depending on the biogas plant geographical location, the used feedstocks and their different shares on a FM basis, and the feedstock management. All these factors are summarized as feedstock supply. Furthermore, the effect of the biogas plants construction, the used machinery and the CHP (biogas utilization) are also considered.

Figure 4 & Table 2 illustrates the calculated GHG emissions (amount & share) in kg CO_2-equivalents (eq) per one kilowatt hour electricity fed into the grid (kWh) for the four case studies. In all four cases the largest share of total CO_2-eq originated from feedstock supply, particularly for Farms 1 and 2. The feeding process, which is included in the sub-system of feedstock supply, depends on the transport distance between the silo and the AD plant. It constitutes a very small fraction of total emissions (0.11 – 0.51%), since RRMs for biogas production were not supplied from other farms in significant amounts.

In second place after feedstock supply come emissions from the CHP unit as methane slip. The biogas production process as a source of mainly direct methane emissions from the AD plant represents the third largest source of CO_2-eq emissions along the process chain, for all four farms. More or less closely behind follow emissions from the operation of machinery and equipment of the biogas plants. Indirect emissions from construction contribute a rather small share in total CO_2-eq emissions, ranging from 1 to 3%. This is because construction processes and machines are approximately used for 20 years.

In comparison with the German grid emissions of 0.523 kg kWh^{-1} (Umweltbundesamt, 2019), the calculated specific CO_2-eq-emissions of electricity production for the four case studies of biogas farms are 29 to 49% lower (Table 1). The lowest total and specific GHG emissions were calculated for Farm 4 (Table 1), according to the highest share of manure as feedstock.

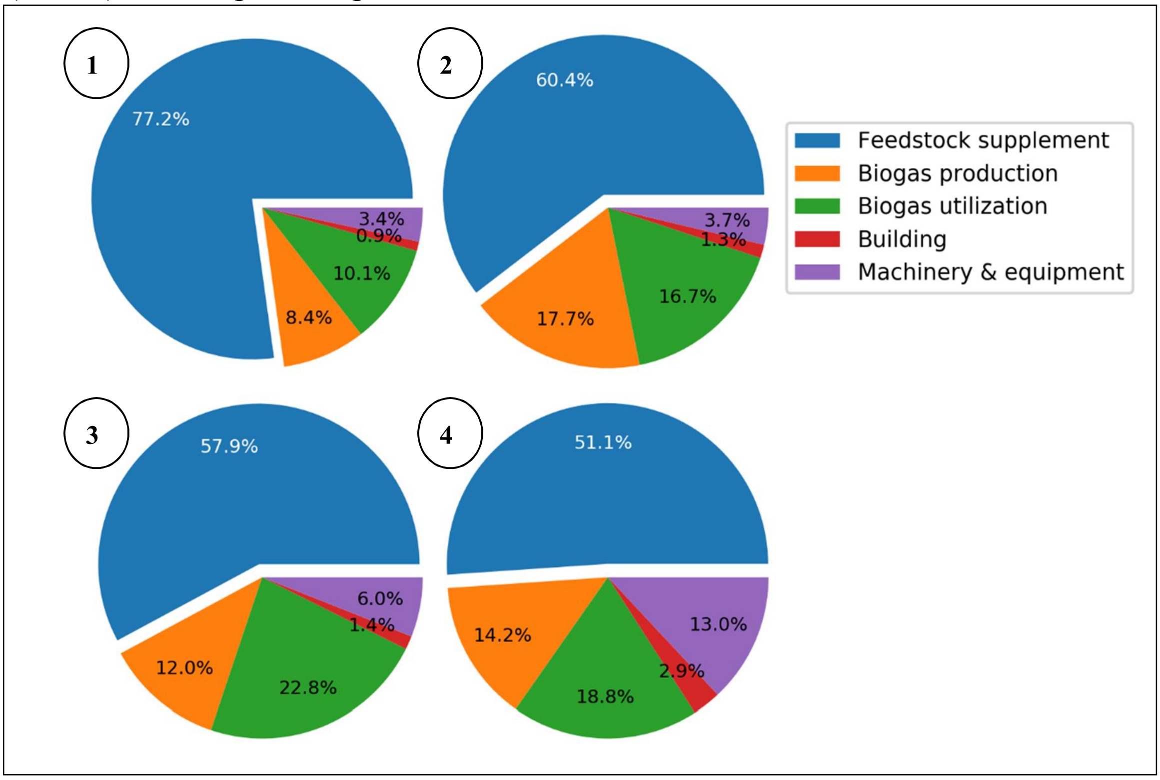

Fig. 4: The share of GHG emissions in the four case studies (1, 2, 3, 4), divided into the different sections of the biogas system

Table 2: Breakdown of calculated CO_2-eq emissions* of electricity supply from the four biogas systems; all values in kg kWh^{-1}.

Section / Farm ID	1	2	3	4
Feedstock supply	0.250a	0.226a	0.161b	0.137b
Biogas production	0.027c	0.066a	0.033b	0.038b
CHP unit	0.033c	0.063a	0.064a	0.050b
Construction	0.003c	0.005b	0.004b	0.008a
Machinery & equipment	0.011c	0.014bc	0.017b	0.035a
Total	0.324a	0.374a	0.280b	0.267b

* Means within each row followed by the same letter are not statistically different at 0.05 level (Duncan's range test).

The heat output of the CHPU was used mainly for heating the digesters and purposes on the farms. By calculating the annual GHG emissions allotted to heat, as it is the default result unit by GaBi®, the results can be compared with other renewable and conventional heat sources. This has been done for Farm 1 as an example (Table 3). The estimated emissions of biogas heat were 128,490 kg $CO_{2\ eq}$/year. The solid biomass displays the lowest annual GHG emissions of 47,602 kg $CO_{2\ eq}$/year with less than the half of emissions from the biogas plant. On the other hand, fossil resources according to GaBi® show huge amounts of annual GHG emissions for the generation of the considered amount of heat, compared to the biogas Farm 1 and solid biomass. Natural gas, liquefied petroleum gas (LPG), heating oil indicate 636,986; 847,419 and 869,707 kg $CO_{2\ eq}$/year respectively, which makes the calculated specific CO_2-eq-emissions of heat generation for Farm 1 is 80 to 88% lower than fossil resources.

Table 3: Comparison of specific GHG emissions (kg CO_{2eq}/year) from heat production for Farm1 with alternative heat sources (GaBi® 6.0 tool database, thinkstep AG, Germany).

Farm1	Solid biomass	Natural gas	Heating oil	LPG
128490.54	47602.68	636986.18	869707.55	847419.18

4. Discussion

The illustrated case studies present specific GHG emissions of electricity production from biogas, divided into the different sections of the biogas system. Given the high shares of RRMs in the input mixes of the biogas farms, the supply of feedstock (Figure 4; Table 2) was significantly the largest source of GHG emissions, with a share of 50 to 77% of total GHG emissions. Farm 4, which showed significantly the highest share of animal manure in the input mix (42%), displayed also the lowest electrical capacity of the CHP unit (100 kW) (Figure 3). On the other hand, the largest share of GHGs from "feedstock supply" was found for Farm1 (95% of which 64% was silage maize), along with the highest electrical capacity of the CHP unit (650 kW). As Scarlat *et al.,* (2018) point out; animal manure has a low specific methane yield of about 6 to 84 l/kg fresh matter, whereas maize silage achieves methane yields of 68 – 170 l/kg. As a consequence, the utilization of energy crops, in particular maize silage for biogas production was expanded significantly over the past years. However, this means that basically the complete environmental footprint of crop production is to be attributed to the energy output of the biogas plants (Britz and Delzeit, 2013).

The construction of the biogas plants in the case studies has a comparably small share in total GHG emissions ranging from 1 to 3%. This is in line with findings from other researchers (*e.g.*, Fuchsz and Kohlheb, 2015; Mezzullo *et al.,* 2013) and is due to the fact that specific impacts from construction are low considering the operational life span of the enterprise, in comparison to the continuous impacts from operation of the AD plant.

Biogas utilization exhibits a considerable share of 10 to 22% of total GHG emissions from our case studies, following second place after feedstock supply. The biogas production system, comprising the AD process, showed slightly lower emissions with a share of 8 to 18% of total GHG emissions. With a range of 8 – 14% the biogas production in Meyer-Aurich *et al.,* (2012) shows always lower GHG emission shares than the biogas utilization (CHP) with a difference ranged between 1 – 11%.

The smallest significant GHG footprint was calculated for Farm 4, with a value of 0.267 kg $CO_{2\text{-}eq}$ kWh^{-1} (Table 2), in accordance with to the largest share of animal manure as feedstock. Neglecting the whole upstream chain of manure production, results in lower emissions along with increasing shares of animal manure as feedstock. The rationale for this approach is that other products in the animal production chain such as milk, meat, leather, tallow, etc. constitute the main economic outputs (Fuchsz and Kohlheb 2015).

The highest significant GHG footprint of electricity production was calculated for Farm 2, with a value of 0.374 kg $CO_{2\text{-}eq}$ kWh^{-1} (Table 3). The high GHG emissions of the organic farm do not commensurate with the principle of the organic farming concept, which aims to alleviate the environmental burden of agricultural production by minimizing negative externalities and generating ecological benefits (Siegmeier *et al.,* 2015). The higher GHG emissions could be a result of: i) the highest number of the used feedstocks (one kind animal manure and six different energy crops; Figure 4), where each one, especially the energy crops, needs separate services such as planting, fertilization (applying the digestate or manure onto the soil), harvest (with 2 grass types managed with many cuts per year), ii) the feedstocks with high contents of lignocellulose (e.g. grass) need larger tanks, more storage capacity, stronger stirring devices (Siegmeier *et al.,* 2015), iii) the cropping management in addition to the lower crop yields of organic farms, requiring significantly larger cultivation area to achieve the same crop yield as conventional farms (Foteinis and Chatzisymeon, 2016). Foteinis and Chatzisymeon, (2016) mentioned that CO_2 emissions of organic farming are lower than from conventional farming, when sustainability was assessed per area (ha) of cultivation. However, at this case the results are different, where conventional cultivation showed a better environmental performance than organic cultivation in terms of CO_2 emissions and total environmental impacts. More research with organic cultivation farms is required.

The differences between the specific GHG emissions of electricity from the German grid mix and the case studies of biogas farms shown in Table 1 are significant, on the one hand, with specific emissions of electricity from biogas 29 to 49% lower than from the grid. On the other hand, the German grid mix in 2018 is still dominated by fossil energy carriers: lignite 23.8%, hard coal 13.5%, natural gas 13.5%, and petroleum products 0.85% (Federal Office of Statistics, 2019). It is therefore obvious that the potential of mitigating GHG emissions by electricity production from biogas mainly produced from energy crops is clearly limited given the continuing rise of electricity production from renewables.

Biogas is also a growing source of heat, reaching about 4% of the heat from bioenergy carriers worldwide in 2015 (Scarlat *et al.,* 2018). The GHG emissions that relate to heat output were calculated only for Farm 1, as an example: The annual GHG emissions for heat from biogas are by a factor of 5 to 6.8 lower compared to fossil fuels; only heat from solid biomass exhibits a smaller GHG footprint. At the same time, the prices for heat from biogas plants are considerably lower than for alternative sources. Balussou *et al.,* (2018) report average revenue for heat sales from biogas plants of 4 ct/kWh, in comparison with the average price for district heating of 7.4 ct/kWh (AGFW, 2019). The biggest challenge of supplying heat from biogas plants is that the heat loss rapidly increases with distance to the end-users.

The utilization of the biogas digesters in Egypt are gaining popularity (Samer, 2012; Thu *et al.,* 2012), where biogas production can help Egypt to sustainably manage biomass waste and produce renewable energy that participate by reducing the GHG emission (Ioannou-Ttofa *et al.,* 2021). Furthermore, the household digesters would also perform an important role and be a beneficial manure management tool (Hou *et al.,* 2017). The results here could be further employed to select the best agricultural biogas system with minimum GHG emissions in Egypt, especially after inaugurating the first project Egypt in 2021 for converting waste into energy through anaerobic gasification in the village of Qalhana, affiliated to Etsa, Fayoum.

5. Conclusions

In this study, four agricultural biogas plants operated in different regions of Bavaria were analyzed to evaluate the impact on global warming from electricity supply. As the feedstock mix on these biogas farms differed in terms of proportions of energy crops versus animal manure, the energy outputs and their GHG footprints also varied significantly. The higher the share of manure in the AD plants, with comparably low biogas yield, the lower the electricity output, and the lower the specific GHG emissions. On the other hand, the higher the share of energy crops as feedstock, the higher the electricity output and the specific GHG emissions from crop cultivation. The results could be further employed to select the best agricultural biogas system with minimum GHG emissions in Egypt.

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