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Eggemann, L.; Rau, F.; Stolten, D.;

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The Ecological Potential of Manure Utilisation in Small-Scale Biogas Plants[1]

Lea Eggemann [a], Florian Rau [b] and Detlef Stolten [a,c]

[a] Institute of Energy and Climate Research – Techno-Economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., 52428 Jülich, Germany
[b] Helmholtz-Zentrum Dresden - Rossendorf e. V., Bautzner Landstraße 400, 01328 Dresden
[c] Chair for Fuel Cells, RWTH Aachen University, c/o Institute for Techno-Economic Systems Analysis (IEK-3),
Forschungszentrum Jülich GmbH, 52428 Jülich, Germany

Lea Eggemann [Corresponding author] - l.eggemann@fz-juelich.de
Florian Rau – f.rau@hzdr.de
Detlef Stolten - d.stolten@fz-juelich.de

Keywords
Life cycle assessment, improved manure management, manure credit, environmental impact, co-product credit, negative emissions

Abstract
The main sources of greenhouse gas emissions, accelerating global climate change, are heat and electricity generation. To lower these emissions, an expansion of renewable energy usage is required. Biogas plants, a flexible renewable power source, are one possibility, and are already widely established in the European energy system. This study focuses on the utilisation of raw manure in closed systems to reduce direct CO_2 eq. emissions. It is the first to compare manure treatment in different types of small-scale biogas applications and under the impact of increasing temperatures resulting from climate change. The environmental impact in terms of four impact categories is evaluated by means of a life cycle assessment. Two cases are investigated: a biogas plant with either subsequent combustion in a combined heat and power plant or the direct usage of biogas as a simplified and less expensive application. The analysis shows that the first case yields -173 kg CO_2 eq. per m³ of manure, whereas the simplified one causes 20.9 kg CO_2 eq. per m³ of manure. If the first case is scaled with the currently existing number of small-manure plants in Germany, emissions of 464 mil. t CO_2 eq. are mitigated per year. With increasing average annual temperatures, higher manure credits are generated and so the emissions of both plant options are

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reduced to -264 and -69.5 kg CO_2 eq. per m³ of manure, respectively, ascribing the direct biogas usage reductions of GHG emissions. Consequently, both systems have the potential for reducing emissions due to improved manure management and can contribute to mitigating climate change.

Abbreviations

AP	Acidification potential
CC	Climate change
CH_4	Methane
CHP	Combined heat and power plant
CO_2	Carbon dioxide
EP	Eutrophication potential
EU	European Union
GHG	Greenhouse gases
ICE	Internal combustion engine
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
NMVOC	Non-methane volatile organic compound
ODP	Ozone depletion potential

1. Introduction

The challenge of combating climate change calls for zero net emissions from the electricity and heat supply [1,2]. Aside from volatile renewable sources like wind and solar energy, bioenergy carries the benefit of being dispatchable. In Europe, almost 19,000 biogas plants represent a viable option for bioenergy as a contributor to electricity and heat production [2]. The majority of biogas plants in the EU is installed in Germany with almost 10,000 plants by October 2021 [3]. The input materials can vary from field crops to organic waste materials. Manure as a waste product of intensive animal farming has become a popular feedstock for biogas plants in recent years, offering the potential of waste material utilisation and energy supply with a low carbon footprint and without competing with food production. German legislation rewards this input material by enhanced remuneration for so-called small-manure plants. These plants have a typical electrical power output between 75 kW and 150 kW and utilise at least 80% manure, and often residues generated by livestock farms such as straw residues [4]. This plant size allows the exploitation of small to common dairy cow farms (e.g. Germany has an average farm size of about 70 cows [5]), while keeping the transport effort at its minimum, as this is an important source of CO_2 emissions [6]. In recent years, a relevant increase in biogas plant construction in Germany has only taken place in the case of small-manure plants. They can contribute especially in terms of decentral energy supply and their numbers increased from 560 plants in 2016 [7] to 1,050 plants in 2021 [8]. Their development has been in accordance with the legislation which requires a shift towards the anaerobic digestion of agricultural residues instead of energy crops [8]. At EU level, this is established in the Renewable Energy Directive 2018/2001, which favours waste materials for the production of biogas [9]. In general, there are large potentials for manure-based biogas production within the EU. Scarlat et al. 2018 [10] estimated an annual amount of 861 million tonnes of collectable manure and a corresponding amount of 30 billion m^3 biogas. The EU had an average installed capacity of 590 kW per biogas plant in 2017. Apart from Germany, smaller capacities can also be found in Denmark and Estonia. Austria and Switzerland have the smallest average capacities with 200 kW [11].

Manure-based biogas plants, and especially small-manure plants, have been the object of study of several life cycle assessment (LCA) studies in the last decade. They were found to generate positive environmental effects in terms of reductions in greenhouse gas (GHG) emissions, in contrast to other feedstocks such as energy crops [12]. One option for LCAs are product-based studies, which measure emissions per m^3 of biogas produced or its energetic value, such as performed by Lansche and Müller [13] and Fuchsz and Kohlheb [14]. A second option can also consider the emissions per input of manure, as the work of Zhang et al. [15], who studied the environmental impact of digesting cow manure. Another study by Hamelin et al. [16] analyzed various co-substrates to manure in an LCA study for Denmark, considering the treatment of one tonne of pig slurry. In general, the advantage of manure is its occurrence as a waste material, which is why upstream processes can be excluded from analyses. This is commonly reflected in LCA studies of biogas systems, as certain steps are placed outside the system boundaries, such as the supply of manure from livestock farming or manure collection and transport [14,15,17,18]. Overall, manure-based biogas plants have the advantage of so-called improved manure management [18]. The system avoids potential methane (CH_4) emissions that occur from conventional manure storage by storing the raw manure in a closed system [19]. As noted by Eggemann [20], various studies account for these avoided emissions in the form of negative CH_4 emissions [12,13,18,21,22]. In general, environmental credits caused by the utilisation of co-products from biogas production such as heat and electricity were found to significantly affect the plants' environmental performance irrespective of their size. An LCA can account for co-products within a system, replacing identical products in the market. This can be performed by using either the concepts of substitution or system expansion in accordance with the ISO 14044 [20]. Biogas plants also generate other types of emissions, particularly acidifying and eutrophication ones, such as equivalents of nitrogen (N), phosphorous (P) and sulphur dioxide (SO_2) emissions. The latter, as well as NO_x emissions contributing to eutrophication, are usually generated by combined heat and power plants (CHPs) [23]. However, in the impact categories of eutrophication and acidification, no relevant differences were found in comparison with conventional manure management [24]. Furthermore, there is agreement in the LCA literature that the GHG balance of biogas plants can be improved by avoiding open digestate storage [13,23,25]. Aside from the use of biogas in internal combustion engines (ICEs) to produce electrical and thermal energy, the avoidance of CH_4 emissions via direct combustion in burners can be a simple and economical means of manure utilisation with a biogas plant [26].

Manure-based plants have also become popular in relation to the idea of closed-production systems or closed nutrient cycling even beyond Europe. For instance, anaerobic digestion operations have expanded in South Africa, as pointed out by Russo and von Blottnitz [27]. The authors analysed the potential to decrease GHG emissions from pork and beef livestock chains per year via anaerobic digestion when utilising electricity and potentially heat from the CHP. The use of small-scale biodigesters and their co-benefits in smallholder farming was examined by Schoeber et al. [28] for optimal farming practices in Ethiopia. In this context, they noted a wide variety of approaches to dealing with digestate and found problems such as open storage and overflow of storage pits. They also point out that biogas is in most cases utilised as a cooking fuel but may also not be utilised at all. Ortiz-Gonzalo et al. [29] evaluated GHG mitigation options in Central Kenya due to agricultural intensification. They found that manure management systems with slurry storage caused higher emissions compared to dry manure storage and emphasised that poor manure management can highly affect a farm's GHG balance [29]. In general, financial and geopolitical barriers are high in many countries with existing feedstock potential but low economic development, making it difficult to establish biogas applications [30].

This study focuses on the decentral utilisation of raw manure to reduce direct emissions of CH_4 with an advanced and expensive, and a simplified and less expensive biogas plant. It builds upon some research conducted as part of a doctoral thesis by Eggemann [20]. The environmental impact of a biogas plant with either subsequent combustion in a CHP or direct usage of the biogas in a simplified burner is investigated in small-scale applications. For the first option, potential savings through the replacement of different types of electricity production in a scenario analysis also come into play. The second option of direct usage is applied wherever heat and electricity can hardly or not at all be utilised, e.g., due to lacking technical knowhow, investment, or missing grid connections. Taking increased CH_4 production from manure under higher ambient temperatures into account [31], the simplified system may be applied to warmer regions with strong economic restrictions or non- or insufficient access to an electrical grid in conjunction with reduced access to advanced technologies. Although LCAs focusing on the environmental performance of classic biogas plants with CHPs have been conducted, this study is the first to compare the emissions of treating manure in classic plants with the option of a system with simple biogas burning, as employed in many countries around the world. Section 2 describes the material and methods, following ISO 14044 [32], section 3 presents and discusses the results and section 4 concludes.

2. Materials and methods

2.1 Goal and scope

The LCA in this study investigates the production of biogas through the utilisation of manure in a biogas plant and further compares combustion in a CHP (case A) with the direct use of biogas by means of simplified combustion (case B). The first case refers to a state-of-art plant design, whereas the second presents a process of direct biogas burning that focuses on the less expensive avoidance of CH_4 emissions of otherwise raw manure. In this study, a small-scale biogas plant is defined as a characteristic small-manure plant with 75 kW. The data was obtained from an existing small-manure plant in Germany which is fed with approximately 10% of straw residues and 90% of liquid manure, both coming from the adjacent dairy cow farm. As measurements were only conducted of the composition of biogas at the plant but not the amount, the quantity of biogas produced is calculated based on the assumptions of the model by Eggemann [20]. Relevant data on the plant's characteristics is summarised in Table 1. The analysis follows the ISO standards [32,33]. For both cases, the functional unit (FU) is 1 m³ of untreated dairy cow manure.

Tab. 1. Biogas plant data including the combined heat and power plant (CHP) adapted from Eggemann [20].

Parameter	Value
Capacity of CHP (kW_{el} │ kW_{th})	75 │ 98
Engine output (kW)	205
Full load hours (h)	8500
Electrical efficiency (%)	36.6
Plant electricity demand (%)	8
Plant heat demand (%)	50
CH_4 content in biogas (vol.-%)	53
CO_2 content in biogas (vol.-%)	46
O_2 content in biogas (vol.-%)	1
Sulfur content in biogas (ppm)	200

The system boundaries are shown in Figure 1. They primarily correspond to the biogas plant, as emissions from the livestock farm are not considered. The systems have a manure pre-storage belowground. The manure flows from the stables into the preliminary storage tank below concrete. Hence, it is assumed that it does not produce emissions once it enters the pre-storage, as also considered by Haenel et al. [34]. The remaining solid feedstock is added directly to the pre-storage. After a short retention time, all of the feedstock is pumped into the digester, where the biogas production takes place, after which the raw biogas is either burnt in a CHP or without further energy utilisation, depending on the case. The application of digestate is not considered, as it is the same for both systems; nevertheless, it could also generate credits for replacing mineral fertiliser. After all, these are comparatively low compared to those of electricity generation [20]. Furthermore, the production of capital goods is not considered because of the relatively small contribution to the overall impact as proven by several studies [5,15,27,28]. Although case A achieves electricity and heat credits generated by the CHP, case B misses out on these, as the burner does not enable the further advanced application of the heat. Three scenarios are introduced in case A for the electricity that is generated by the CHP. In a system expansion, it is assumed to replace the German grid mix (grid), wind (wind) and coal-based (coal) electricity to tackle the issue of multi-functionality within the system, following the reasoning in Eggemann et al. [12]. The case of wind-based electricity replacement serves as representative for an energy system based on 100% renewables, whereas the coal-based electricity replacement represents a fossil-based energy system. The German grid mix with 27% of renewable electricity production in 2014 [35] represents an example that lies within these extremes and represents the proportion of renewables that can be achieved in economic and grid stability terms. German heat generation is also replaced but not varied, as there is no significant difference between relevant types [12].

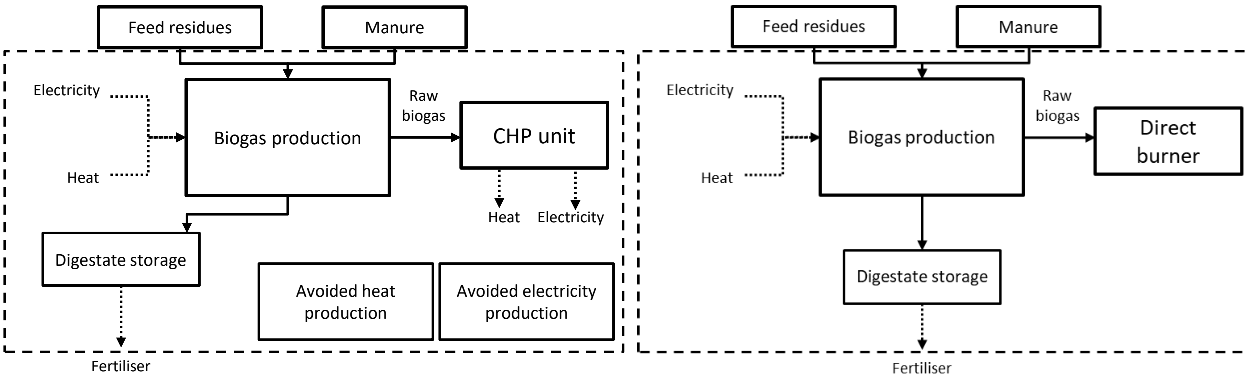

Figure 1. System boundaries of the biogas plant with combined heat and power plant (CHP) (left, case A) and direct burner (right, case B) adapted from Eggemann [12].

2.2 Life cycle inventory

The life cycle inventory (LCI) uses data and some assumptions already introduced in part for the biogas plant within the Power-to-Fuel system analyzed in Eggemann et al. [19], which are briefly summarized in this section. Table 2 displays the LCI, which is calculated for the FU of 1 m³ of manure. Data for foreground processes comes from either the plant itself or is calculated using values from the literature fitting well with the plant's characteristics. Background data is used to determine the impacts for heat and electricity production from Ecoinvent version 3.5 [35]. For case A, heat is supplied by the CHP and therefore not taken from the market. The feedstock utilized was approximately 90% of dairy cow manure as well as 10% of agricultural residues. As these substrates are waste materials from an adjacent livestock farm, zero emissions are assumed. In both cases, CH_4 and ammonia (NH_3) emissions occur during biogas production from leakages in the fermenter and digestate storage. Nitrous dioxide (N_2O) emissions are neglected due to data scarcity, in accordance with the IPCC [31]. The amount of NH_3 leaking from the fermenter is below 0.05% of the nitrogen (N) in the digestate, and can therefore also be excluded [36,37]. The NH_3 emissions occurring during storage are included, making up 2.66% of the N in the digestate [36]. CH_4 losses of 0.534 kg/h are recorded for case A, mainly deriving from the incomplete combustion within the CHP [6,38]. The digestate storage, even though it is not gas-tight, is assumed to generate negligible CH_4 emissions due to the long retention time of 150 days inside the fermenter, which significantly reduces the residual gas potential [39]. The manure credit, i.e., the CH_4 that is credited to the system in both cases, is based on emissions per dairy cow head and year for manure management in liquid/slurry and pit storage systems according to the emission factors provided by the IPCC [31]. In this study, the credit is calculated and considered in the assessment at two different temperatures; for the average annual temperature of <10 °C as in central Europe and for 25 °C to simulate a more temperate region. The latter results in much higher emissions, i.e., 75 kg/head*year instead of 21 kg/head*year [31]. Thus, the savings from improved manure management would be higher. The emissions were calculated for 126 cows that provide manure on-site. This study assumes an excess of raw manure, as is currently still available. Only one third of German manure has been utilised in biogas plants so far [40]. Emissions for the CHP for case A were measured at the biogas plant in November of 2018 as two-hour average values and are supplied in the supplementary material in Table S1. In contrast to the CHP, the combustion of biogas inside a burner causes no CH_4 emissions. The process was simulated in Aspen Plus to clarify that the CH_4 is entirely converted to CO_2 and H_2O, and is therefore not contained in the flue gas. This was done with an equilibrium calculation based on the conditions at the CHP inlet. The other considered emissions cannot be used from the calculation since the equilibrium is unlikely achieved. Therefore, values from the literature are applied. The nitrogen emissions of the direct burner are lower, compared to the CHP, due to a continuous combustion and therefore problems of e.g. ignition limits are less distinct, which would allow a shift of the equivalence ratio to leaner combustion. The literature, such as El Helou et al. [41] and Józsa et al. [42], show possible lower limits for the NO_x emissions of 10 - 15 mg/Nm³ flue gas with high effort. The legal limits e.g. in Germany require values below 120 mg/Nm³. Also considering burners on the market a value of 55 mg/Nm³ was chosen. The same way of decision leads to an emission of 215 mg/Nm³ for sulphur oxides [43], 35 mg/Nm³ for carbon monoxide [41,42,44] and 10 mg/Nm³ for NMVOC [41,45]. A flue gas stream of 259 m³/h, calculated for the CHP, is also assumed for the burner for reasons of comparison. The CO_2 contained in the flue gas is assumed to be biogenic and is therefore excluded from the inventory in both cases.

Table 2. Life cycle inventory for case A (combined heat and power plant = CHP) and case B (direct burner).

Biogas production					
INPUT		**OUTPUT CASE A**		**OUTPUT CASE B**	
Manure (m^3)	1.00	Biogas (m^3)	133.01	Biogas (m^3)	133.01
Electricity (MJ)	74.06	NH_3 emission (kg)	0.06	NH_3 emission (kg)	0.06
Heat (MJ) (only case B)	604.80	Manure credit (kg/h)	-1.04	Manure credit (kg/h)	-1.04
Utilisation in CHP and direct burner					
INPUT		**OUTPUT CASE A**		**OUTPUT CASE B**	
Biogas (m^3)	133.01	Electricity (MJ)	925.71	Electricity (MJ)	0
		Heat (adjusted for own consumption) (MJ)	604.80	Heat (MJ)	0
		Emissions		**Emissions**	
		CO (kg)	0.61	CO (kg)	0.03
		NMVOC (kg)	0.01	NMVOC (kg)	0.01
		CH_4 (kg)	1.83	CH_4 (kg)	0
		NO_x (kg)	1.14	NO_x (kg)	0.05
		SO_2 (kg)	0.19	SO_2 (kg)	0.19

2.3 Life cycle impact assessment

The characterisation method, 'ReCiPe 2016', for calculating impacts, is used at the midpoint level [46] from the GaBi Life Cycle Engineering Suite [47]. It is a suitable method for the assessment of manure-based biogas systems that considers the impacts within a 100-year time-frame [23]. Five impact categories were chosen for the comparison of the two cases, A and B. The emissions of kg CO_2-eq. were calculated for the category of climate change (CC) and kg NO_x eq. for ozone depletion potential (ODP), as these emissions are interesting for comparisons across regions [23]. Other evaluated categories include eutrophication potential for marine and freshwater (EP) in kg N-eq. and kg P-eq., respectively, as well as acidification potential (AP) in kg SO_2-eq. These were selected in accordance with Esteves et al. [23], as they are commonly evaluated in combination with biogas systems due to the high content of nutrients in manure. These nutrients can also negatively affect the environment when not properly handled.

3. Results and discussion

The results for the CHP (case A) underline the potential of small-manure plants to reduce climate change (CC) by treating manure in biogas systems. The scenario with replaced coal-based electricity shows, with -317.00 kg CO_2 eq., the greatest reduction in the category of CC for 1 m^3 of manure. This is followed by -173.00 kg CO_2 eq. for replacing grid mix electricity, whereas replaced wind electricity generates -5.83 kg CO_2 eq. The latter is due to the comparatively low electricity credits of -3.84 kg CO_2 eq. which only account for 8% of the impacts. As can be seen in Figure 2 (left), the type of replaced electricity makes a relevant difference. The electricity credits are the highest for replacements in a coal-based energy system, as there is more improvement in CO_2 eq. emissions in comparison to the grid mix and wind-based electricity. Here, the electricity credits make up 67% of the impacts. The direct use of biogas (case B) does not receive energy credits, as in case A, which results in emissions of 20.90 kg CO_2 eq. The emissions caused by the energy demand of the fermenter of 56.30 kg CO_2 eq. outweigh the manure credits of -35.40 kg CO_2 eq. Case A thus performs 7 and 14 times better in the grid and coal scenarios, respectively, compared to direct biogas burning. The complete results of the impact assessment can be found in Table S2 in the supplementary material.

When increasing the annual mean temperature up to 25 °C, the manure credits become higher and cause emission reductions in all scenario variations of case A. The results are presented in Figure 2. There is only a difference in CC, as it is the only category in this study that accounts for CH_4 emissions. The other categories are therefore not affected. The coal scenario improves to -408.00 kg CO_2 eq., the grid scenario to -264.00 kg CO_2 eq. and the wind scenario would also yield emissions of -96.30 kg CO_2eq. In addition, the dependence on the type of replaced electricity remains the same. The impact trend changes for case B at higher temperatures, as now, the emissions become negative and yield -69.50 kg CO_2 eq. per m³ of manure treated in the biogas system (Figure 2, direct usage). This shows that in such an environment, the direct use of biogas would even be beneficial without a CHP. Given that the heat demand of a biogas plant may also be lower in more temperate climates, an improved CC impact would be possible. The overall CO_2 eq. emissions for direct biogas use would then be -112.30 kg CO_2 eq. per m³ if no heating was required by the fermenter at all. Consequently, the environmental savings in terms of CO_2 eq. would be greater than those for the wind scenario in case A.

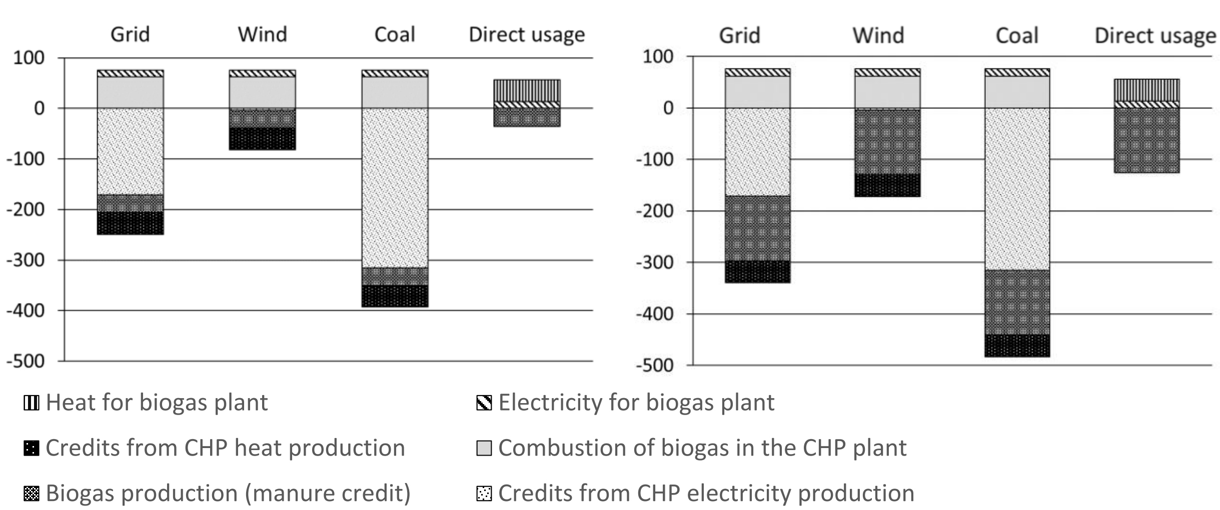

Figure 2. Results of the life cycle impact assessment for the category of climate change (CC) [kg CO_2 eq.] for average annual temperatures of <10 °C (left) and 25 °C (right).

The impact assessment results of the remaining categories of marine and eutrophication potential (EP), acidification potential (AP), and ozone depletion potential (ODP) are shown in Figure 3. The impact assessment results for EP are very similar for marine and freshwater, as they are connected to each other. Moreover, they exhibit similar outcomes as CC, namely a reduction in emissions from the best (wind) to worst case (coal). This is again caused by the increasing credits for replaced electricity generation, as can be overserved in Figure 3. In the coal scenario, environmental credits from the replaced electricity generation account for 97.4% of the total impacts in freshwater EP, i.e. yielding emissions of -0.73 kg P eq. Emissions by the grid scenario account for -0.23 kg P eq., which translate into environmental savings, whereas the replaced wind electricity yields emissions of 1.64-E02 kg P eq. Case A performs 10 to 35 times better than the direct use. However, the direct utilisation, which causes emissions of 2.04E-02 kg P eq., performs slightly worse, with 20% more kg P eq. The coal scenario achieves the lowest impact values for marine EP with -4.65E-02 kg N eq., followed by -1.52E-02 kg N eq. in the grid scenario. The outcomes of the wind scenario are environmental burdens of 8.68E-04 kg N eq., which are 64% of the kg N eq. of 1.37E-03 generated by treating 1 m^3 of manure in a system of direct usage. For the wind scenario, it means that an additional 2.22 kg N eq. are emitted to the environment per year, whereas the other scenarios yield emissions of -118.81 kg N eq. and -38.84 kg N eq., respectively. To put these values in relation, the German *Düngeverordnung*, a regulation on the application of fertilisers, allows an annual amount of applied N in soils of 170 kg/ha per farm [48].

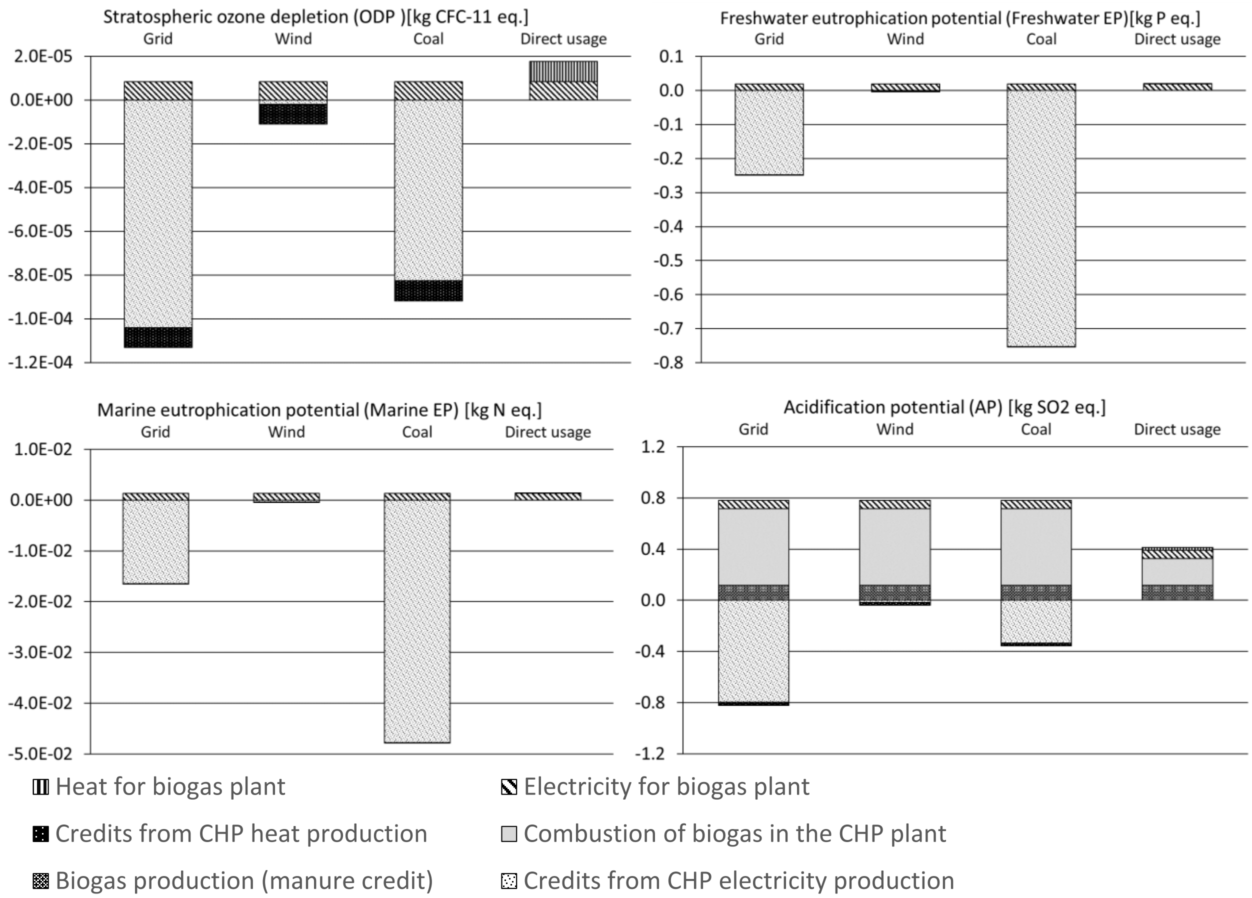

Figure 3. Results of the life cycle impact assessment for the categories of stratospheric ozone depletion, freshwater and marine eutrophication potential and acidification potential.

Considering ODP, the CHP performs four to five times better for the scenarios of grid and coal, with emissions of -1.05E-04 kg CFC-11 eq. and -8.35E-05 kg CFC-11 eq., respectively, compared to the direct utilisation. The wind scenario yields emissions of -2.76E-06, where the kg CFC-11 eq. emissions caused by the electricity demand of the biogas plant can be offset by the electricity credits. However, in case B, which yields environmental burdens of 1.75E-05 kg CFC-11 eq., there are no credits to offset the emissions caused by the energy demand of the biogas plant. If there was no heat required, as is likely the case in warmer climates, the direct utilisation would generate half of the burdens. This is due to the fact that about half of the emissions are caused by the heat and half by the electricity demand of the biogas plant. The environmental credits in both the ODP and AP improve from the coal to grid scenario, indicating greater emissions in the grid mix per MJ for grid mix electricity, as was already concluded by Eggemann et al. [49]. The AP generates environmental burdens in the coal and wind scenarios as expected, causing 0.42 kg SO_2 eq. and 0.74 kg SO_2 eq. emissions. However, the grid scenario generates -0.04 kg SO_2 eq. caused by the electricity credits which account for 50% of the emissions. On the other hand, case B yields emissions of 0.41 kg SO_2 eq., similar to those of the coal scenario and only 55% of those of the wind scenario. This is due to the lower direct SO_2 eq. emissions of the burner compared to the CHP.

In summary, the performance of each case not only depends on the type of energy that the CHP replaces but also on the local conditions such as the energy demand of the biogas plant and the average annual temperatures. The CHP would currently save approximately 442 t CO_2 eq. per year under central European climate conditions for a total of 2,600 m^3 manure arising at the livestock farm adjacent to the biogas plant. This would mean that a small-manure plant, as the one investigated, could contribute significantly to CC mitigation at the current stage. Under these assumptions, a total of 1,050 small-manure plants in Germany, as of December 2021 [8], would mitigate about 464 mil. t CO_2 eq. emissions per year. When a carbon price of 80 €/t is assumed, as the average price since December 2021 (as of June 2022), one biogas plant could receive 35,400 €/a of additional earnings for case A with the grid scenario and the lower annual ambient temperature. It may be used to compensate the additional efforts for CHP maintenance and operation. If energy systems with an increased amount of coal-based electricity apply case A, the savings would be as high as approximately 810 t CO_2 eq. per biogas plant per year. The annual emissions would add up to 54 t CO_2 eq. per small-manure plant for direct biogas usage, causing additional environmental burdens. However, these still lie significantly below the 74 t CO_2 eq. emissions from conventional manure management for the same number of cows as in combination with the analysed biogas plant.[2] It should be noted that the European context imposes certain limits on the comparability of the results in this study in a global context, as the source of CH_4 emissions from conventional manure management is assumed to be slurry in pit storage systems. In other regions of the world, raw manure could be handled differently, e.g., in solid form or may not even be treated at all. This could affect the environmental credits from improved manure management in terms of CO_2 eq. emissions when considering the numbers presented by the IPCC [21]. However, in regions with similar manure management techniques as in Europe, and with higher average annual temperatures, the credits become much higher, saving 674 t CO_2 eq. annually for the CHP replacing grid-mix electricity. In comparison, the emissions from conventional manure management at higher temperatures generate emissions of 265 t annually for 126 dairy cows.[3] Direct usage under such conditions would then also generate savings of 178 t CO_2 eq. If heating of the fermenter was not necessary, a small-manure plant with direct biogas usage would even save emissions of 287 t CO_2 eq. per year. Therefore, at higher temperatures both cases provide emission reductions, meaning that improved manure management can become even more relevant under the aspect of rising temperatures due to climate change.

[2] Simplified calculation of 74.1 t/a CO_2 eq. emissions according to the IPCC [31] for a number of 126 cows with a factor of 28 for CH_4; other emissions, such as N_2O etc, are not taken into account.

[3] Same simplified calculation as in [2] for a mean annual temperature of 25°C instead of <10°C.

4. Conclusions and outlook

In conclusion, the study found that improved manure management can mitigate emissions from raw manure storage significantly. It was shown that the average annual temperature influences the biogas plant's impact on climate change. A comparison of two manure-based biogas systems indicates relative improvements for a classic biogas plant as opposed to the direct combustion of biogas, even if the manufacturing and operation of CHPs require an elaborated effort. Electricity and heat from a CHP could become even more relevant in countries with a fossil-dominated energy supply. If average annual temperatures are higher and/or energy demand by the fermenter decreases, the direct usage generates benefits through the avoided CH_4 emissions due to improved manure management and a cleaner burning process. Therefore, if conventional manure management occurs in warmer regions or temperatures increase, biogas systems could become more relevant in terms of manure credit. While the direct usage has an advantage over the CHP by entirely avoiding CH_4 emissions, classic biogas plants are able to offset these with their credits for heat and electricity. The emissions data from the CHP under consideration employs a gas Otto engine without a catalyst. Therefore, the use of a catalytic converter would further reduce the CO_2 eq. emissions of the CHP and the use of an activated carbon filter would reduce the SO_2 eq. emissions. It should also be pointed out that the data used in this study is tailored to one type of small-manure plant in Germany to represent an existing plant instead of average values from the literature. Nevertheless, in order to enable a more in-depth analysis about a wide variety of plant concepts with different storage systems, varying numbers of fermenters and retention times as well as different types of CHPs could be taken into account. As a 100% renewable energy system on a global scale is unlikely to be achieved in the short or medium term, biogas plants offer significant potential for reducing emissions from manure management in intensive livestock farming. In a future study, this may be re-evaluated under the consideration of economic aspects in order to further investigate emission reductions, trade-offs and the compliance with climate targets.

Declarations of interest

The authors indicate that all funding bodies have been acknowledged and there are no conflicts of interests in publishing this research paper.

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Supplementary material

Table S1. Emissions for the combined heat and power plant measured in Germany in November of 2018 as two-hour average values with a Fourier-transform infrared spectroscopy (FTIR) and converted to dry exhaust gas with 5 vol.-% oxygen and 273 K.

Emissions in air	Clean gas [mg/Nm³]	ppm	Emission factor (out) [kg/TJ]	Emission factor (in) [kg/TJ]	Calculated hourly emissions [kg/h]
SO_2	214.97	73.35	206.21	74.23	0.06
NO_x	1289.00	627.97	1236.45	445.12	0.33
CO	685.00	547.79	657.07	236.55	0.18
NMVOC	14.73	12.57	14.13	5.09	0.00
CO_2	301036.25	152262.54	288763.97	103955.03	77.97
CH_4	2063.00	2875.31	1978.90	712.40	0.53

NMVOC: Non-methane volatile organic compound

Table S2. Results of the LCIA for case A and the scenarios of the grid mix, wind and coal as well as for case B for the categories climate change (CC), stratospheric ozone depletion (ODP), marine and freshwater eutrophication (EP) and acidification potential (AP); n.a. = not applicable.

	Total	Credits from CHP electricity production	Biogas production (manure credit)	Combustion of biogas in the CHP plant/direct burner	Credits from CHP heat production	Electricity for biogas plant	Heat for biogas plant
				Case A - grid			
CC [kg CO_2 eq.]	-173.000	-171.000	-35.400	62.200	-42.600	13.700	n.a.
EP freshwater [kg P eq.]	-2.28E-01	-2.47E-01	0.00	0.00	-6.19E-04	1.97E-02	n.a.
EP marine [kg N eq.]	-1.52E-02	-1.64E-02	0.00	0.00	-5.04E-05	1.32E-03	n.a.
ODP [kg CFC-11 eq.]	-1.05E-04	-1.04E-04	0.00	0.00	-9.19E-06	8.35E-06	n.a.
AP [kg SO_2 eq.]	-0.039	-0.798	0.118	0.600	-0.022	0.064	n.a.
				Case A - wind			
CC [kg CO_2 eq.]	-5.830	-3.840	-35.400	62.200	-42.600	13.700	n.a.
EP freshwater [kg P eq.]	1.64E-02	-2.69E-03	0.00	0.00	-6.19E-04	1.97E-02	n.a.
EP marine [kg N eq.]	8.68E-04	-3.97E-04	0.00	0.00	-5.04E-05	1.32E-03	n.a.

ODP [kg CFC-11 eq.]	-2.76E-06	-1.91E-06	0.00	0.00	-9.19E-06	8.35E-06	n.a.
AP [kg SO_2 eq.]	0.742	-0.017	0.118	0.600	-0.022	0.064	n.a.
Case A - coal							
CC [kg CO_2 eq.]	-317	-315	-35.4	62.2	-42.6	13.7	n.a.
EP freshwater [kg P eq.]	-7.32E-01	-7.52E-01	0.00	0.00	-6.19E-04	1.97E-02	n.a.
EP marine [kg N eq.]	-4.65E-02	-4.78E-02	0.00	0.00	-5.04E-05	1.32E-03	n.a.
ODP [kg CFC-11 eq.]	-8.35E-05	-8.27E-05	0.00	0.00	-9.19E-06	8.35E-06	n.a.
AP [kg SO_2 eq.]	0.424	-0.335	0.118	0.6	-0.0223	0.0639	n.a.
Case B							
CC [kg CO_2 eq.]	20.900	n.a.	-35.400	0.00	n.a.	13.700	42.600
EP freshwater [kg P eq.]	2.04E-02	n.a.	0.00	0.00	n.a.	1.97E-02	6.19E-04
EP marine [kg N eq.]	1.37E-03	n.a.	0.00	0.00	n.a.	1.32E-03	5.04E-05
ODP [kg CFC-11 eq.]	1.75E-05	n.a.	0.00	0.00	n.a.	8.35E-06	9.19E-06
AP [kg SO_2 eq.]	0.412	n.a.	0.118	0.208	n.a.	0.064	0.022