

Economic and environmental performance of miscanthus cultivated on marginal land for biogas production

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Abstract

Environmental issues surrounding conventional annual biogas crops have led to growing interest in alternative crops, such as miscanthus. In addition to the better environmental performance, miscanthus can be grown on marginal land where no competition with feed and food crops is anticipated. On marginal land however, biomass yields are significantly lower than on good agricultural land. This raises the question of the economic and environmental sustainability of miscanthus cultivated on marginal land for biogas production. This study assessed the environmental and economic performance of miscanthus cultivated on marginal land for biogas production by conducting a Life-Cycle Assessment and complementary Life-Cycle Cost analysis. The functional unit chosen was 1 GJ of electricity (GJ_{el}). The substitution of a fossil reference was included using a system expansion approach. Electricity generated by the combustion of miscanthus-based biogas in a combined heat and power has considerably lower impacts on the environment than the fossil reference in most of the categories assessed. In the impact category “climate change”, the substitution of the marginal German electricity mix leads to a carbon mitigation potential of 256 kg $\text{CO}_2\text{e}/\text{GJ}_{\text{el}}$. At 45.12 €/GJ_{el}, the costs of miscanthus-based biogas generation and utilization are considerably lower than those of maize (61.30 €/GJ_{el}). The results of this study clearly show that it can make economic and environmental sense to cultivate miscanthus on marginal land as a substrate for biogas production. The economic sustainability is however limited by the biomass yield. By contrast, there are no clear thresholds limiting the environmental performance. The decision needs to be made on a case-by-case basis depending on site-specific conditions such as local biodiversity.

KEYWORDS

biogas, environmental performance, LCA, LCC, marginal land, miscanthus, production cost

1 | INTRODUCTION

Climate change is one of the most pressing environmental issues of our time. According to the IPCC's Fifth Assessment Report (AR5), the 30-year period from 1983 to 2012 was probably the warmest in the Northern Hemisphere in the last 1,400 years (IPCC, 2014). A large part of the emissions responsible for climate change are released from industrial processes in the form of fossil CO₂ emissions. The combustion of fossil fuels in particular plays a major role in these processes (IPCC, 2014). A promising option to reduce these negative impacts is the substitution of fossil with biobased energy sources (McKendry, 2002).

One example of biobased energy sources is biogas, which is produced by the anaerobic digestion of dedicated energy crops, manure or waste (Weiland, 2010). Various studies have shown that the production and subsequent combustion of biogas for heat and electricity generation has a significant carbon mitigation potential when substituting a fossil reference (Kiesel, Wagner, & Lewandowski, 2016; Lansche & Müller, 2012; Rehl, Lansche, & Müller, 2012). In 2016, over 18 million tonnes of GHGs were avoided through the use of biogas in Germany alone (FNR, 2017), with dedicated energy crops being the main input substrate. Their share of total substrate use (based on mass) was 51.2%, of which 73% was maize silage (FNR, 2017). However the cultivation of maize is associated with several environmental pressures including the risk of soil erosion and compaction, nitrate leaching and high pesticide use (European Environment Agency, 2006).

For this reason, there is growing interest in alternative biogas crops, such as miscanthus (Kiesel & Lewandowski, 2017; Kiesel et al., 2017; Mayer et al., 2014). Miscanthus is a perennial rhizomatous C₄ grass which originates from South East Asia (Clifton-Brown, Schwarz, & Hastings, 2015). It is a low-input crop with high nitrogen, land-use and energy efficiency (Lewandowski & Schmidt, 2006). After a 2-year establishment phase, it can be harvested annually over a cultivation period of up to 20 years (Lewandowski, Clifton-Brown, Scurlock, & Huisman, 2000). The long-term soil rest and the input of biogenic carbon to the soil, for example, through harvest residues, leads to soil carbon accumulation and soil fertility improvement (Dondini, Hastings, Saiz, Jones, & Smith, 2009; Lal, 2016; McCalmont et al., 2017). In addition to its favourable environmental performance, miscanthus has the major advantage over conventional annual biogas crops that it can be cultivated on marginal land, where no competition with feed and food crop cultivation is anticipated (Lewandowski et al., 2016). In Europe, the genotype *Miscanthus × giganteus* is predominantly cultivated. However, much breeding effort is currently being directed at developing new genotypes with higher abiotic stress tolerance, for example to salinity or drought (Lewandowski et al., 2016). Stress-tolerant genotypes are required in particular for

the production of miscanthus biomass on marginal land with bio-physical constraints to crop production (Lewandowski et al., 2016).

Besides biogas production, miscanthus biomass can also be used in a number of other biobased value chains such as the production of bioethanol (Lee & Kuan, 2015), heat and power via combustion (Baxter et al., 2014), building materials (Uihlein, Ehrenberger, & Schebek, 2008) and bio-composites (Ogunsona, Misra, & Mohanty, 2017). For these purposes, miscanthus biomass is harvested when senescent and dry. By contrast, for use as a biogas substrate, a green harvest is conducted in late autumn. On good agricultural land in temperate regions, yields of around 26 t DM ha⁻¹ year⁻¹ are achievable (Kiesel & Lewandowski, 2017). This corresponds to a methane yield of about 4,500–5,000 m³ CH₄ year⁻¹ ha⁻¹, which is comparable to maize (Kiesel et al., 2016).

The environmental performance of the use of miscanthus as a biogas substrate has been comprehensively analysed in several different impact categories for various genotypes and climatic conditions (Kiesel et al., 2016; Wagner, Kiesel, Hastings, Iqbal, & Lewandowski, 2017). However the economic performance of miscanthus-based biogas production has not yet been holistically assessed. Most studies focus on the costs of miscanthus production and do not assess the whole value chain (Khanna, Dhungana, & Clifton-Brown, 2008; Wang, Wang, Hastings, Pogson, & Smith, 2012; Witzel & Finger, 2016). For other biogas crops that have been assessed, the biomass supply—including biomass cultivation, harvesting and transport—had a huge influence on the costs of biogas production (Stürmer, Schmid, & Eder, 2011). Walla and Schneeberger (2008) assessed the costs of electricity production from biogas based on the fermentation of maize silage. In their study, they demonstrated that, depending on the scenario analysed, the biomass supply costs can account for up to 50% of total costs (Walla & Schneeberger, 2008).

Miscanthus production costs are strongly influenced by the biomass yield (Wang et al., 2012). In addition, variations in yield have been shown to have a significant impact on the environmental performance of miscanthus-based value chains (Meyer, Wagner, & Lewandowski, 2017). It has been shown that, when miscanthus biomass is used for combustion in a combined heat and power plant, a dry matter yield increase of 1 t leads to a carbon mitigation potential increase of around 1.5 t CO₂e (Meyer et al., 2017). Therefore, biomass yield is a key factor for both the economic and environmental performance. However, on marginal sites, achievable yields are often lower than on good agricultural land (Dauber et al., 2012). There may be a critical yield level below which environmental benefits, for example, GHG reduction, become negligible or even negative. At this point, the benefits of biomass production need to be considered. This consideration is also relevant in the light of other environmental aspects of biomass production on marginal land, such as the impact

on biodiversity. Thus, the question arises whether miscanthus cultivation on marginal land and the subsequent utilization in a biogas plant to generate heat and electricity is sustainable in economic and environmental terms.

To answer this question and assess the environmental performance of miscanthus-based biogas production, a Life-Cycle Assessment (LCA) was conducted according to the ISO standards 14040 and 14040 (ISO, 2006a,b). The economic performance was analysed in a complementary Life-Cycle Cost (LCC) assessment in accordance with Swarr et al. (2011). The data for the miscanthus cultivation were based on a field trial with different miscanthus genotypes on a marginal site at *Unterer Lindenhof*, a research farm of the University of Hohenheim. The specific methane yield of the miscanthus biomass was assessed in the laboratory. The data for investment and operational costs as well as the technical characteristics of the farm's biogas plant were drawn from the literature. Background data on emissions and costs associated with input substrates (e.g., fertilizer), machine use and transport processes were taken from the ecoinvent database 3.4 (Wernet et al., 2016) and from the KTBL database (KTBL, 2018).

2 | MATERIALS AND METHODS

2.1 | Goal and scope

The scope of this study is a cradle-to-grave analysis of the environmental and economic performance of miscanthus cultivation on marginal land and subsequent fermentation of the biomass in an anaerobic digestion plant. The biogas generated in the plant is used in a combined heat and power (CHP) unit with the generation of electricity as its main product and heat as a by-product. The functional unit chosen was 1 GJ of electricity (GJ_{el}). The environmental and economic performance was then compared with a fossil reference using a system expansion approach. The fossil reference chosen was the "marginal" German electricity mix. "Marginal" technology is defined according to Rehl et al. (2012) as the "technology or the technology mix, which is substituted by a new technology under consideration of market aspects and technology specific availability".

2.2 | Methods

The environmental performance of miscanthus cultivation was assessed by conducting a LCA according to the ISO standards 14040 and 14040 (ISO, 2006a,b), using the life-cycle impact assessment methodology ReCiPe (Huijbregts et al., 2017). The selection of the relevant impact categories was based on Wagner et al. (2017). They analysed the relevance of various impact categories in the assessment of miscanthus-based value chains and recommended the

inclusion of climate change (CC)—which corresponds to global warming potential—agricultural land occupation (ALO), human toxicity (HT), marine (MET) and freshwater ecotoxicity (FET), as well as marine (ME) and freshwater eutrophication (FE) (Wagner et al., 2017).

To calculate the biomass supply costs, all costs incurred over the entire 20-year cultivation period were included. To take the time factor into account, the costs of each year were discounted to their present value separately applying a discount rate of 6%. These included all costs related to the production and transport of input substrates (e.g., fertilizer), the agricultural management of the miscanthus and the transport from the field to the biogas plant. The total discounted costs were used to calculate the corresponding annual costs. These were divided by the average annual biomass yield (see Table 2) to give the biomass supply costs per tonne of biomass produced.

All investment, operational and capital costs for the biogas production and subsequent utilization in a combined heat and power plant were taken into account. The lifetime of the biogas plant was assumed to be 20 years, the lifetime of the installations and machinery 8 years (Leible, Kälber, Kappler, Oechsner, & Mönch-Tegeger, 2015). In addition, constant costs for the replacement of installations and machinery within the lifetime of the biogas plant were assumed. For the capital costs, an annual interest rate of 6% was applied.

2.3 | System boundaries

The system assessed in this study is displayed in Figure 1. The system boundaries include the production and transport of input substrates, such as herbicides, propagation material and fertilizer, and the agricultural management over the crop's entire 20-year lifetime. In the first year, miscanthus is mulched and then, from the second year onwards, it can be harvested annually. The recultivation of the site at the end of the cultivation period was included in the study. After harvest with a self-propelled forage harvester, the biomass is transported to the biogas plant and ensiled there for storage. The silage is subsequently fermented in an anaerobic digestion plant to biogas, which is combusted in a CHP to produce electricity and heat. The fermentation residues contain a considerable amount of nutrients and can be used to substitute mineral fertilizer, which is also considered in this study.

2.4 | Life-cycle inventory

2.4.1 | Agricultural system

The data for the miscanthus cultivation were based on a field trial described in detail by Mangold et al. (2018a). The trial

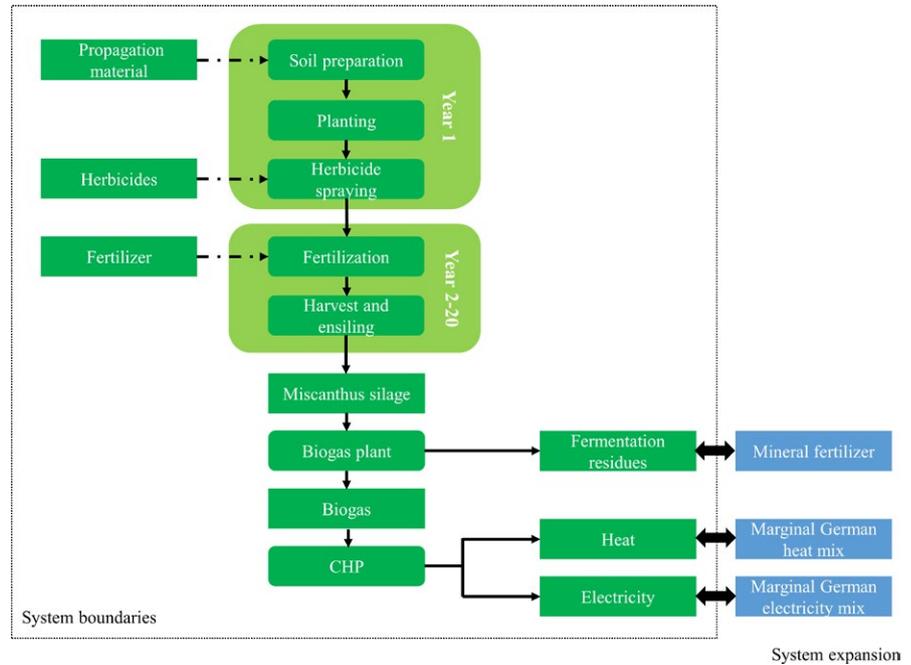


FIGURE 1 System description and boundaries for miscanthus cultivation, fermentation to biogas and subsequent utilization in a combined heat and power to generate heat and electricity

was performed at the *Unterer Lindenhof*, a research station of the University of Hohenheim. Here, miscanthus is cultivated on a marginal site to be used as biogas substrate in the farm's biogas plant. This site is considered marginal in bio-physical terms because of a high clay and stone content, as well as waterlogged soils. These bio-physical constraints lead to a poor workability and trafficability of the soil and therefore favour the cultivation of perennial crops as here planting and soil cultivation is only necessary in the first year. Before planting the miscanthus rhizomes, soil preparation was carried out twice with a rotary harrow and once with a plough. The rhizomes were planted at the beginning of May with a planting density of two rhizomes per m^2 .

Data for herbicide application were taken from Wagner et al. (2017). Herbicide application is usually only necessary in the first 2 years and in the recultivation process. A typical application regime over the whole cultivation period can be described as follows: 10 L/ha Round up (Monsanto, active ingredient 360 g/L glyphosate); 3.5 L/ha Stomp Aqua (BASF, active ingredient 455 g/L pendimethalin); 1.5 L/ha Calisto (Syngenta, active ingredient 100 g/L mesotrione); 0.2 L/ha Arrat (BASF, active ingredient 100 g/L tritosulfuron and 500 g/L dicamba); and 1 L/ha Dash, (BASF, an emulsifiable concentrate) (Wagner et al., 2017). Based on a cultivation period of 20 years, this corresponds to an average of 0.81 L herbicides per hectare and year.

The fertilization rate was calculated based on the nutrient removal rate of the harvested biomass to avoid soil depletion. The nutrient content of the biomass harvested green in autumn as a percentage of dry matter yield was as follows: 0.42% nitrogen (N), 0.45% potassium (K) and 0.04% phosphorus (P), based on the field trial described

in Mangold et al. (2018a). This corresponds to a fertilizer demand of $76 \text{ kg N ha}^{-1} \text{ year}^{-1}$, $81 \text{ kg K ha}^{-1} \text{ year}^{-1}$ and $7 \text{ kg P ha}^{-1} \text{ year}^{-1}$. It was assumed that all input substrates are transported 150 km from their production sites to the farm by truck. The yield data used were based on the whole cultivation period including the establishment phase where the biomass is not harvested but mulched. This calculation is described in more detail in Wagner et al. (2017). The methane yield was measured based on the approach described in Kiesel and Lewandowski (2017). Table 1 summarizes the agricultural operations, including frequency, which were used in this study during the entire miscanthus cultivation period. Table 2 shows the main inputs and outputs of miscanthus cultivation.

It was assumed that, after harvest, the biomass is transported over a distance of 5 km by tractor to the biogas plant. This transport distance is in line with other studies (Bacenneti,

TABLE 1 Summary of agricultural operations during a 20-year miscanthus cultivation period

Agricultural operation	Frequency per cultivation period
Rotary harrow	2
Plough	1
Planting	1
Mulching-first year	1
Herbicide spraying	5
Fertilizing	19
Harvest	19
Mulching-final year	1
Chisel plough	1

TABLE 2 Summary of main inputs and outputs of miscanthus cultivation per year

Input/output	Amount	Unit
N	76	kg year ⁻¹ ha ⁻¹
P	7	kg year ⁻¹ ha ⁻¹
K	81	kg year ⁻¹ ha ⁻¹
Herbicide	0.81	l year ⁻¹ ha ⁻¹
Dry matter yield	18,034	kg year ⁻¹ ha ⁻¹
Dry matter content	43.4	%
Methane yield	4,704	m ³ CH ₄ year ⁻¹ ha ⁻¹

Fusi, Negri, Guidetti, & Fiala, 2014; Kiesel et al., 2016; Walla & Schneeberger, 2008). However, the use of marginal land for the cultivation of biogas crops could lead to higher transport distances in future (Liu et al., 2011). For this reason, a sensitivity analysis was conducted to assess the influence of this assumption on the final result. It was assumed that the biomass is ensiled at the biogas plant with dry matter losses of 12% (KTBL, 2013).

Fertilizer-induced emissions during cultivation were estimated as follows. Direct N₂O and NO emissions from nitrogen fertilizer were calculated based on Bouwman, Boumans, and Batjes (2002). Indirect N₂O emissions from nitrogen fertilizer and N₂O emissions from harvest residues were estimated according to IPCC (2006). Nitrogen fertilizer-induced ammonia emissions were calculated based on emission factors from EMEP/CORINAIR (2001). Phosphate and phosphorus emissions to surface and groundwater as well as heavy metal emissions to agricultural soils were calculated according to Nemecek and Kägi (2007). The heavy metals contained in the harvested biomass were not included in the calculation, as they are later returned to the soil in the digestate used as fertilizer. Nitrate leaching to groundwater was estimated based on the SQCB-NO₃ model described in Faist Emmenegger, Reinhard, and Zah (2009). All pesticides applied were modelled completely as emissions to agricultural soil according to Nemecek and Schnetzer (2011). The respective ecotoxicity values are taken from the ecoinvent database (Wernet et al., 2016).

The costs of machinery and diesel used in the agricultural operations were taken from the KTBL database (KTBL, 2018). Labour costs for the agricultural system were based on the working time requirements for each agricultural operation as specified by KTBL (2018). Labour costs of 17 € per working hour were assumed based on the German agricultural labour agreement and calculations by the North Rhine-Westphalia chamber of agriculture (Landwirtschaftskammer Nordrhein-Westfalen & RLV e.V., 2017). These 17 € also include incidental wage costs. The annual land rent per hectare of 328 € was based on the average cost of agricultural land in Germany in the year 2016 (Statistisches Bundesamt, 2017b).

This is a conservative assumption as the land rent for marginal land is probably lower. Land opportunity costs of 322 € per hectare were assumed. The opportunity costs are based on the contribution margin of an average crop rotation in Baden-Württemberg (LEL, 2016). Background data on costs associated with the production and the transport of input substrates (e.g., fertilizer) were taken from the ecoinvent database 3.4 (Wernet et al., 2016). The costs of biomass transport were assumed to be 0.1 € t⁻¹ km⁻¹ based on Hastings et al. (2017).

2.4.2 | Anaerobic digestion

It was assumed that the miscanthus silage is mechanically pretreated with a cross-flow grinder before fermentation. It has been shown that such pretreatment increases the methane yield of lignocellulosic substrates such as miscanthus (Frydendal-Nielsen et al., 2016; Mönch-Tegeder, Lemmer, Jungbluth, & Oechsner, 2014). The cross-flow grinder has an energy consumption of 12 kWh_{el} per tonne of fresh matter (Mönch-Tegeder et al., 2014).

The biogas plant assessed in this study was based on Lansche and Müller (2012). The main characteristics of the plant are summarized in Table 3. The proportions (based on mass) of the biogas substrates were 90% miscanthus silage and 10% liquid cattle manure (Lansche & Müller, 2012). It was assumed that the necessary amount of liquid cattle manure is available on-farm without any costs or additional environmental burden. Further, it was assumed that 1.73% of the methane produced is emitted as diffuse methane emissions, mainly in the exhaust air from the combustion systems (Liebetrau et al., 2010). This assumption is in line with other studies assessing the environmental performance of biogas production and utilization in a CHP (Rehl & Müller, 2013).

As a system expansion approach was applied, it was assumed that the electricity generated in the CHP substitutes the marginal German electricity mix. With respect to the by-product, 18% of the total heat produced is used internally to heat the fermenter (Lansche & Müller, 2012). It was assumed that 50% of the remaining heat (which corresponds to 41% of the total heat produced) is used to heat nearby buildings and thus substitute the marginal German heat mix (see Table 4). These are the fossil fuels which, according to the German Federal Environmental Agency, are most likely to be substituted through an increase in energy generated from biogas plants (UBA, 2017). In the environmental and the economic assessment, credits are given for the amount of fossil-based heat which is substituted. These credits represent the environmental burden and economic costs associated with the generation of the marginal German electricity mix.

The fermentation residues are rich in nutrients and can be used to substitute mineral fertilizer. However, here only the nutrients from the miscanthus biomass were taken into account. The nutrients brought into the system through the liquid cattle

TABLE 3 Main technical characteristics of the biogas plant

Technical characteristic	Value	Unit
Full load hours	7,800	hr/year
Plant output, electrical	500	kWh _{el}
Plant output, total	1,219	kWh
Electrical efficiency	40	% of plant total output
Thermal efficiency	43	% of plant total output
Inherent heat demand	18	% of total heat production
Inherent power consumption	10	% of total power production

TABLE 4 Marginal German heat and electricity mix (UBA, 2017)

Fossil fuel	Marginal German heat mix in %	Marginal German electricity mix in %
Oil	56.3	0
Gas	43.3	35
Hard coal	1.3	65

manure were not included, as they will be applied as fertilizer to the feed crops for the cattle. The phosphorus and potassium contained in the miscanthus biomass can be fully recovered through the use of the fermentation residues as fertilizer. However, only 70% of the nitrogen compounds contained in the fermentation residues is plant-available (Börjesson & Berglund, 2007; Kiesel et al., 2016; Lansche & Müller, 2012); thus, only 70% were taken into account. In accordance with Lansche and Müller (2012), it was assumed that the mineral fertilizers with the highest domestic sales in Germany are substituted. In 2016, these were calcium ammonium nitrate for N, super phosphate for P and potassium chloride for K (Statistisches Bundesamt, 2017a). In the environmental and the economic assessment, credits are given for the mineral fertilizers which are substituted. These credits represent the environmental burden and economic costs associated with the production of the respective amount of mineral fertilizers.

All cost data for the pretreatment of the biomass (including investment, operational and labour costs) are based on an existing cross-flow grinder used by the University of Hohenheim's research biogas plant at the *Unterer Lindenhof* for the pretreatment of lignocellulosic biomass (Leible et al., 2015). The costs of the biogas plant and the CHP are based on the 500 kWh_{el} plant described in Leible et al. (2015).

2.5 | Sensitivity analysis

Three sensitivity analyses were conducted to assess the influence of important parameters on the final results. Both

changes in transport distance and changes in biomass yield were assessed. As it has been found that the utilization of heat has a significant impact on the final results (Kiesel et al., 2016), a sensitivity analysis was also conducted to assess the influence of different heat utilization options on the environmental and economic performance of miscanthus-based biogas production and utilization.

3 | RESULTS

The results of the life-cycle impact assessment are presented first, followed by the LifeCycle Cost analysis and finally those of the three sensitivity analyses.

3.1 | Life-cycle impact assessment

For the seven impact categories assessed, the environmental impacts are given per GJ electricity generated, including the substitution of the fossil reference. Thus negative values are net benefits, whereas positive values are net-negative impacts caused by the substitution of the fossil reference through the biobased alternative. The value chain assessed in this study was divided into six process steps. The process step *Agricultural production* includes the production and transport of input substrates such as fertilizer, as well as all agricultural operations including harvest of the biomass. *Transport biomass* comprises the transport of the biomass from the field to the biogas plant. The process step *Biogas plant operations* includes the ensiling of the biomass, pre-treatment with a cross-flow grinder, anaerobic digestion and combustion of the biogas in a CHP. *Substitution fertilizer* encompasses the credits given for the substitution of mineral fertilizers through the nutrients contained in the fermentation residues. *Substitution heat* refers to the substitution of the marginal German heat mix, *Substitution electricity* the substitution of the marginal German electricity mix.

Figure 2a shows the results for the impact category “agricultural land occupation” (ALO) in m²*year. The main impact stems from the cultivation of miscanthus on marginal land.

Figure 2b shows the results for the impact category “climate change” (CC) in kg CO₂eq. The results are dominated by the credits given for the substitution of the marginal German electricity mix. Main emission sources are fertilizer production and fertilizer-induced emissions in the process step *Agricultural production* and diffuse methane emissions in *Biogas plant operations*.

The results for the impact category “freshwater ecotoxicity” (FET) are presented in Figure 2c, for “human toxicity” (HT) in Figure 2d and for “marine ecotoxicity” (MET) in Figure 2e. The cultivation of miscanthus and the subsequent utilization in a biogas plant leads to a net benefit in all three impact categories, mainly due to the substitution of the marginal German electricity mix.

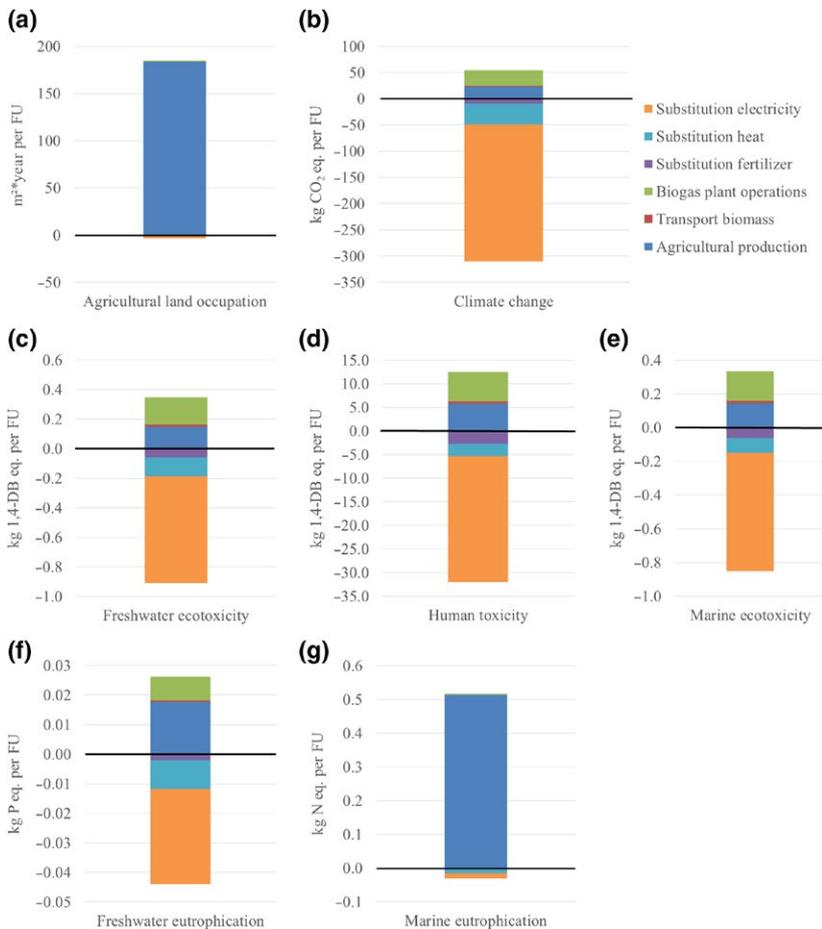


FIGURE 2 (a) Agricultural land occupation, (b) climate change potential, (c) freshwater ecotoxicity, (d) human toxicity and (e) marine ecotoxicity potential, (f) freshwater eutrophication and (g) marine eutrophication potential per functional unit of the cultivation of miscanthus and subsequent utilization in a biogas plant generating heat and electricity. The results shown include the substitution of the fossil reference

Figure 2f shows the results for the impact category “freshwater eutrophication” (FE). In this category, the substitution of fossil energy through the utilization of miscanthus biomass in a biogas plant leads to a net benefit. The impacts in the step *Agricultural production* are mainly caused by phosphate and phosphorus emissions to surface and groundwater through the use of P fertilizer.

The results for the impact category “marine eutrophication” (ME) are given in Figure 2g. The emissions responsible for the impact in the process step *Agricultural production* are mainly nitrate emissions caused by the use of mineral nitrogen fertilizer.

3.2 | Life-Cycle Cost analysis

The Life-Cycle Costs per GJ electricity generated are displayed in Figure 3. The costs of biomass supply comprise costs for production and transport of input substrates (e.g., fertilizer), for all agricultural operations including harvest and for transport to the biogas plant. The establishment phase of the miscanthus is responsible for the largest share of these costs. The costs of the pretreatment are mainly caused by the investment and operating costs of the cross-flow grinder. The biogas plant operation costs are, for the most part, investment costs. In total, it costs 50.95 € to generate 1 GJ of electricity. Inclusion of the substitution of mineral fertilizers

and of the marginal German heat mix leads to a decrease in total costs down to 45.12 €/GJ_{el}. (see Figure 3).

3.3 | Sensitivity analysis

Three sensitivity analyses were conducted to assess the influence of changes in key parameters (biomass yield, transport distance and heat utilization rate) on the economic and environmental performance.

3.3.1 | Biomass yield

The annual biomass yield of around 18 t dry matter per hectare used in the assessment was based on measured yields from a field trial on marginal land (Mangold et al., 2018a). However, other studies have shown that miscanthus yields can be significantly lower depending on the site conditions and the genotype cultivated (Iqbal & Lewandowski, 2014; Meyer et al., 2017). Therefore, the sensitivity analysis assessed how the economic and environmental performance changes when the biomass yield decreases. Figure 4 shows how the results in the assessed impact categories increase when the annual biomass yield decreases to 15, 12, 9 and 6 t dry matter per hectare. If the substitution of fertilizer, heat and electricity is included, the influence of these changes

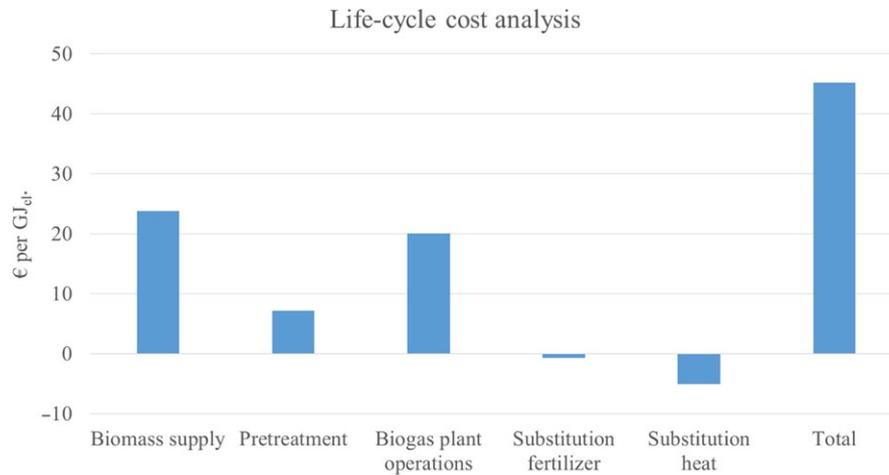


FIGURE 3 Life-Cycle Costs per GJ_{el} of miscanthus cultivation and subsequent utilization in a biogas plant generating heat and electricity

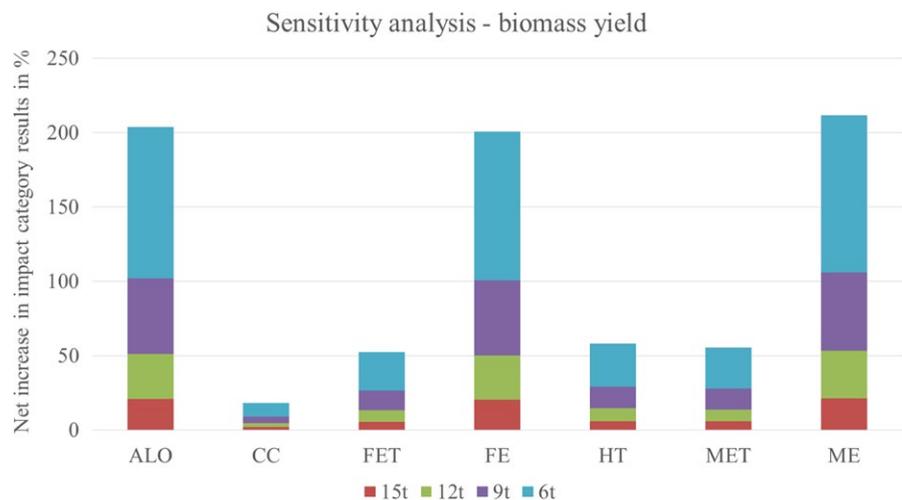


FIGURE 4 Sensitivity analysis—Effect of changes in biomass yield (presented in t DM ha⁻¹ year⁻¹) on environmental performance

is pronounced, especially for the impact categories agricultural land occupation, freshwater eutrophication and marine eutrophication. As these three impact categories are mainly dominated by the agricultural system, changes in the biomass yield have a profound effect. For example, when the dry matter yield decreases to 6 t per hectare, the ALO potential increases by more than 200% (from 180.9 to 549.2 m³/GJ). However, it should be noted that the effects of variations in biomass yield do not change an impact into a benefit or vice versa, except in the impact category freshwater eutrophication. From a yield level of 9 t or lower, the substitution of the fossil reference leads to a net impact on the environment in the respective category. In the impact categories climate change, freshwater and marine ecotoxicity as well as human toxicity a decrease in the yield level leads to a lower benefit when the substitution of a fossil reference is included.

The influence of changes in biomass yield on economic performance is displayed in Figure 5. The costs per GJ electricity increase significantly with lower biomass yield.

3.3.2 | Transport distance

In the baseline scenario, an average transport distance of 5 km from the field to the biogas plant was assumed. A sensitivity analysis was conducted to assess the influence of this assumption on the final results. Figure 6 shows the effect of longer transport distances (10, 20, 30, 40, 50 km) on the impact categories assessed in this study. When substitution of the fossil reference is included, the influence on the results is significant, particularly in the impact categories freshwater and marine ecotoxicity, human toxicity and freshwater eutrophication (Figure 6). However, it should be noted that the effects of variations in biomass yield do not change an impact into a benefit or vice versa.

Figure 7 shows the influence of longer transport distances (10–50 km) on the costs per GJ electricity generated. In this transport distance range, the impact of the increased transport costs on the total production costs is comparatively small.

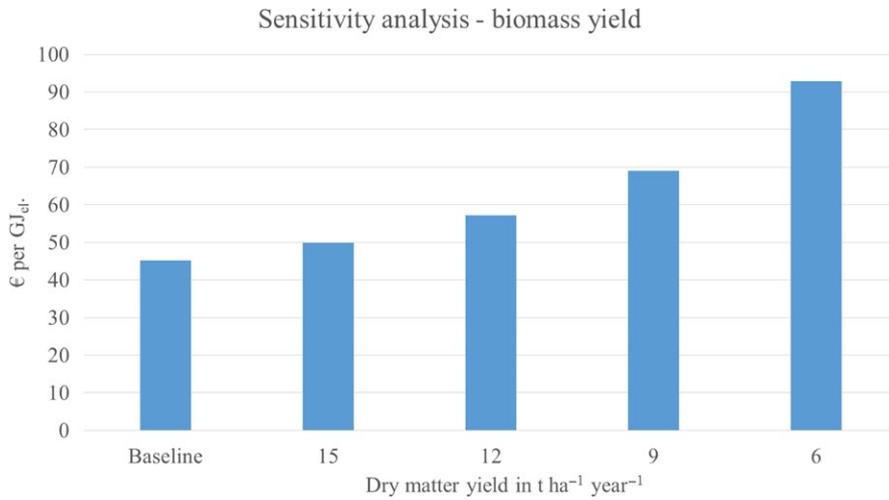


FIGURE 5 Sensitivity analysis—Effect of changes in biomass yield on economic performance

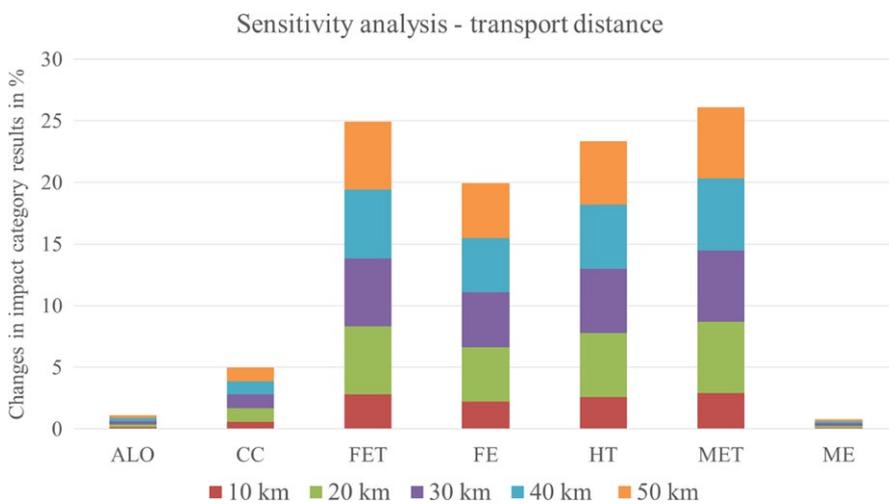


FIGURE 6 Sensitivity analysis—Effect of changes in transport distance on environmental performance

3.3.3 | Heat utilization rate

It was assumed in the assessment that 50% of the available heat is used to heat nearby buildings, substituting the marginal German heat mix. A sensitivity analysis assessed the influence of a change in heat utilization rate on the final results. Thus in addition to 50%, heat utilization rates of 0%, 25%, 75% and 100% were also analysed (Figure 8). An increase in the heat utilization rate leads to a decrease in the analysed impact categories and thus to a better environmental performance.

The influence of changes in the heat utilization rate on the costs per GJ electricity generated is shown in Figure 9. An increase in heat utilization rate leads to a significant decrease in the total costs per GJ electricity generated.

4 | DISCUSSION

This section begins with a critical analysis of the environmental and economic performance of miscanthus-based biogas

production and the subsequent combustion in a CHP. The results of the current study are also compared with both the standard biogas crop maize and a fossil reference. In addition, possible trade-offs between environmental impact categories as well as between environmental impacts and costs are discussed and the main hotspots and potential improvements highlighted. The second part of the discussion focuses on the question under which conditions biogas from miscanthus grown on marginal land makes sense from an environmental and economic point of view. Here, also other aspects such as biodiversity are included, as these need to be considered in the decision to cultivate biomass crops on marginal land.

4.1 | Environmental and economic performance of miscanthus-based electricity production compared to alternatives

Electricity generated by the combustion of miscanthus-based biogas in a CHP has considerably lower impacts on the environment than the fossil reference in most categories

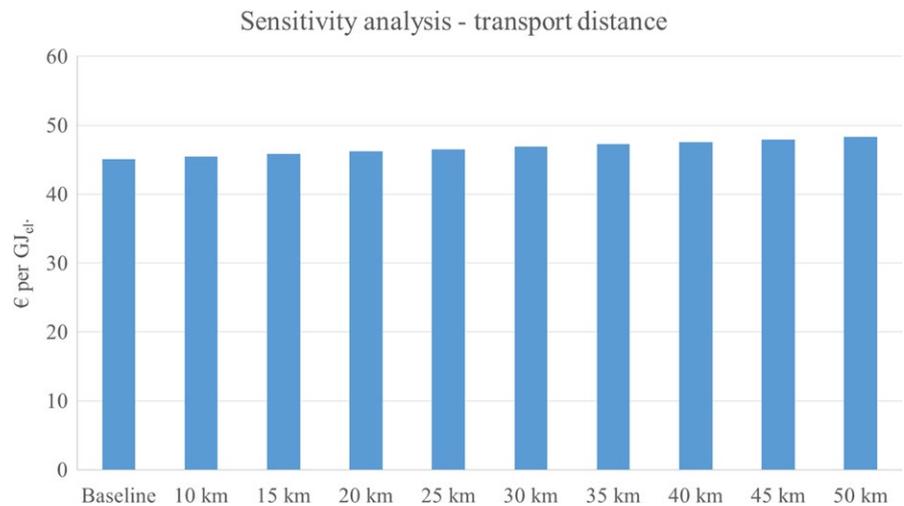


FIGURE 7 Sensitivity analysis—Effect of changes in transport distance on economic performance

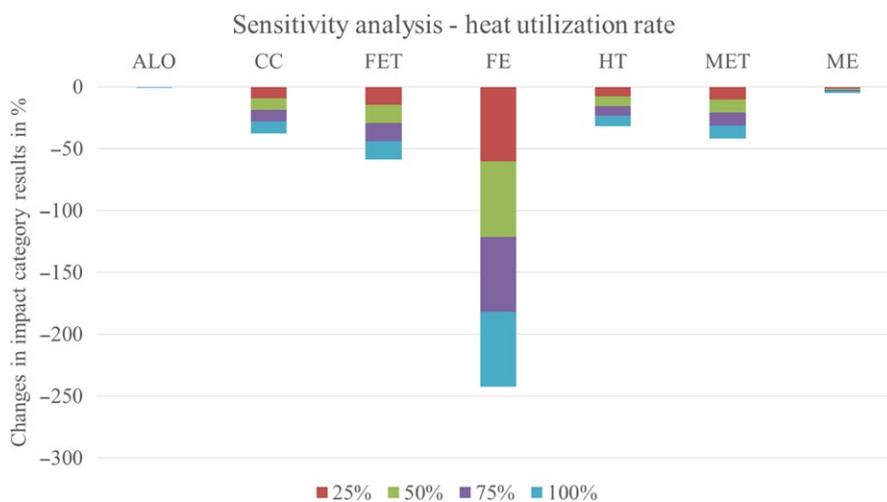


FIGURE 8 Sensitivity analysis—Effect of changes in heat utilization rate on environmental performance

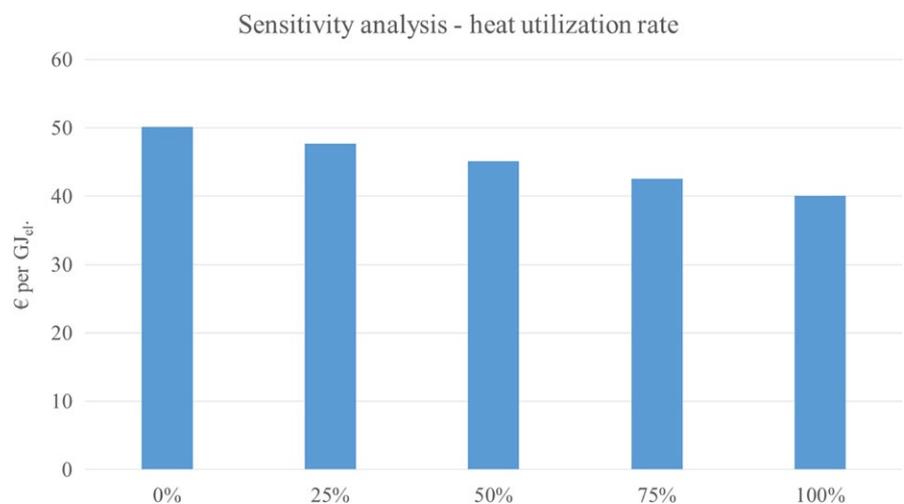


FIGURE 9 Sensitivity Analysis—Effect of changes in heat utilization rate on economic performance

assessed in this study. The substitution of the marginal German electricity mix leads to substantial net benefits in the impact categories HT, MET, FET, FE and CC. In two categories, marine eutrophication and agricultural land

occupation, the impact of the miscanthus-based biogas production is significantly higher than the fossil reference (see Figure 2). Thus there is a clear trade-off between different environmental impact categories. The marine

eutrophication potential is mainly caused by nitrate leaching through the use of nitrogen fertilizers. The amount of nitrogen fertilizer applied in the system under study was based on the nutrient removal by the harvested biomass. Therefore a further reduction should not be considered in the LCA in order to not increase the risk of depleting nitrogen levels in the soil. However, miscanthus requires much less nitrogen fertilizer than annual crops including the standard biogas crop maize (Kiesel et al., 2016). As a result, the nitrate leaching under miscanthus is significantly lower in comparison to annual crops such as maize (Christian & Riche, 2006; Davis et al., 2012; Lesur et al., 2014). Also, there are several reports that nitrogen fertilization does not increase miscanthus yields (Christian, Riche, & Yates, 2008; Himken, Lammel, Neukirchen, Czymionka-Krause, & Olf, 1997), which is probably an effect of nutrient recycling within the crop and the good nitrogen uptake from the soil by the perennial crop. Consequently a change from annual to perennial biogas crops would considerably decrease the environmental impact in the category marine eutrophication.

The impact category agricultural land occupation indicates the area of land required for the cultivation of miscanthus in order to produce 1 GJ of electricity. As virtually no agricultural land is required for the fossil reference, there is a clear negative impact on the environment when the marginal German electricity mix is substituted by electricity generated through combustion of miscanthus-based biogas in a CHP. This also applies to other biogas crops such as maize. There is a strong negative correlation between the impact category agricultural land occupation and the biomass yield. The agricultural land occupation increases with a decrease in biomass yield, as it is the case with marginal land where biomass yields are low. Consequently, in comparison to good agricultural land, a larger marginal site is necessary to support a biogas plant of the same size. However, in the impact category agricultural land occupation no distinction is made on the quality of the land used. Thus a direct comparison between the use of good agricultural land, on which food crops could also be cultivated, and marginal land, with possibly no other economically viable utilization option, is not possible. For this reason, it may still be beneficial to use marginal land for the cultivation of perennial biogas crops, even if more land is required in comparison to annual biogas crops cultivated on good agricultural land, as there is no risk of displacing food or feed crops.

The establishment of perennial grasses such as miscanthus can have tremendous effects on the soil organic carbon (SOC) content and thus also on the global warming potential. These changes are strongly dependant on the former land-use type (Harris, Spake, & Taylor, 2015). It was shown that there are no effects on the SOC when miscanthus is established on former grassland (Don et al., 2012; Zatta, Clifton-Brown,

Robson, Hastings, & Monti, 2014). If former arable land is used, there is a 0.7–2.2 t C ha⁻¹ year⁻¹ increase in SOC content (McCalmont et al., 2017). This corresponds to 2.6–8.1 t CO₂ ha⁻¹ year⁻¹. As marginal land is highly diverse, the influence of changes in SOC was not included in this paper due to the high uncertainties associated. However, as miscanthus establishment in most cases has either no effect or a positive effect on the SOC content, this can be considered a worst-case assumption.

In general it can be said that, to improve the environmental performance of miscanthus-based biogas production and subsequent combustion in a CHP, the focus should be put on high biomass yields. An increase in yield significantly decreases the impact of biomass production on the environment and therefore improves the environmental performance of the whole biobased value chain (Meyer et al., 2017). The genotype *Miscanthus × giganteus* is only partially suitable for the cultivation on marginal land due to its low cold and drought stress tolerance. New, recently developed genotypes with higher abiotic stress tolerance should come onto the market in the coming years. These offer a promising opportunity to increase biomass yield on marginal land and subsequently decrease the impact on the environment (Lewandowski et al., 2016). In addition, a huge potential for improvement lies in the diffuse methane emissions during the biogas plant operations, where methane is mainly emitted in the exhaust air from the combustion system. More frequent maintenance, the use of a catalytic converter and the afterburning of the exhaust could considerably reduce these methane emissions and thus reduce the greenhouse gas emissions of the whole process (Liebetrau et al., 2010).

The baseline scenario with a dry matter yield of 18 t results in farm-gate production costs for miscanthus biomass of 55.79 € per t DM, which is in line with other studies (Wang et al., 2012b). The electricity produced through the combustion of miscanthus-derived methane is with 45.12 €/GJ_{el}, slightly more expensive than other renewable energy sources such as photovoltaic systems and onshore wind power (ISE, 2018). However the main advantage of biogas-based electricity is that, in contrast to the other more fluctuating renewable energy sources, it can function as a base load provider. One promising option for the use of miscanthus is the substitution of maize as a substrate in existing biogas plants. It has already been shown that miscanthus' environmental performance as a biogas crop is more favourable than that of maize (Kiesel et al., 2016). However, for the farmer or biogas plant operator, the economic performance plays a major role in the decision which biogas substrate to use. Estimated electricity generation costs using maize as biogas substrate are 56.57 €/GJ_{el}. This figure is based on average substrate costs of 42.20 € per tonne of fresh matter (Agostini et al., 2016), which is in line with other studies (Gebrezgabher, Meuwissen, Prins, & Lansink, 2010), a methane hectare yield of 5,594 m³

CH_4 year⁻¹ ha⁻¹ (Kiesel et al., 2016), and a biogas plant with the same technical characteristics as in the current study. In this calculation, pretreatment with a cross-flow grinder is not included as this is not necessary for maize. In addition, the credits given for the substitution of fertilizer are slightly higher as maize-based fermentation residues have a higher nutrient content than miscanthus-based ones. However, the biomass supply costs are considerably higher for maize in comparison to miscanthus. As the result, at 45.12 €/GJ_{el}, the costs determined in this study using miscanthus as a biogas substrate are significantly lower than for the scenario using maize. In the scenario described above, it was assumed that maize is cultivated on good agricultural land. This setting was chosen as in Germany energy maize is mostly cultivated on such sites. If maize is cultivated on marginal land, the yield is significantly lower and shows higher fluctuations than on good agricultural land (Ehmann, Thumm, & Lewandowski, 2018). In this case, the cost advantage of miscanthus would be much more pronounced.

Consequently, from an economic point of view, it would make sense to use miscanthus in place of maize as a biogas substrate. However, the area under miscanthus cultivation is still relatively low. One important barrier to the implementation of miscanthus can be seen in the high initial investment costs for farmers associated with the establishment phase.

The establishment costs are mainly caused by the costs of the rhizomes. These rhizomes cost around 0.175 € each (Wernet et al., 2016) which corresponds to 3,500 € per hectare with a planting density of 2 plants per m². Currently, the sole commercially available genotype *Miscanthus × giganteus* can only be propagated via rhizomes. However, in recent years, breeding research has focused on the development of novel seed-based genotypes (Clifton-Brown et al., 2017; Iris Lewandowski et al., 2016). Through the use of these new seed-based hybrids, it would be possible to reduce establishment costs significantly (Clifton-Brown et al., 2017; Hastings et al., 2017).

In the current study, pretreatment using a cross-flow grinder was included. It was shown that nearly 60% of the costs associated with the pretreatment of the miscanthus biomass using a cross-flow grinder are labour costs. A decrease in labour requirements, for example, through further automation of the pretreatment system, could reduce pretreatment costs significantly. In addition, Mangold et al. (2018b) showed that the ensiling of miscanthus biomass reduces the necessary intensity of pretreatment. Besides the economic performance, this would also improve the environmental performance of miscanthus-based biogas production.

The current study demonstrated that miscanthus has a favourable environmental performance and that its substitution of the marginal German electricity mix leads to net

benefits in several impact categories. The use of miscanthus as a biogas substrate is also less expensive in comparison to the standard biogas crop maize. Therefore improvements in economic and environmental performances are not contradictory. Increasing the yield or decreasing the intensity of the pretreatment, for example, reduces costs and at the same time improves the environmental performance of the whole value chain. The results shown are based on field trials where miscanthus was cultivated on marginal land. However, depending on the type of marginal land used, the achievable biomass yield is often lower (Iris Lewandowski et al., 2016; Meyer et al., 2017) and the transport distance longer (Dauber et al., 2012) than those used in the current study. The results of the sensitivity analysis showed that changes in transport distance and especially in biomass yield have a significant influence on the environmental and economic performance. Therefore the question arises under which conditions biogas production using miscanthus cultivated on marginal land is economically and environmentally sustainable.

4.2 | Preconditions for an economically and environmentally sustainable biogas production using miscanthus cultivated on marginal land

As shown above, electricity generation costs using miscanthus as biogas substrate are 45.12 €/GJ_{el}, compared to 61.30 €/GJ_{el} for maize. This cost advantage for miscanthus decreases with decreasing yields. A miscanthus yield of around 11 t DM/ha gives electricity generation costs comparable to those of maize. If the yields were even lower, it would be more economical to use maize as biogas substrate. However, it has to be kept in mind that if miscanthus is cultivated on such marginal land, the land rent and the opportunity costs for foregone profit would also be lower. The influence of transport distance and heat utilization rate and thus location of the biogas plant are of lesser importance.

The substitution of the marginal German electricity mix through electricity generated by the combustion of miscanthus-based biogas in a CHP leads to net benefits in the impact categories HT, MET, FET, FE and CC. This is still the case when the biomass is transported over longer distances, the yields are lower, or a lower heat utilization rate is applied. Except for freshwater eutrophication, none of the impact categories that were positive for miscanthus-derived electricity became negative with decreasing biomass yield or increasing transport distance. Therefore, no yield threshold could be derived from this study below which it does not make sense from an environmental point of view to produce miscanthus on marginal land.

In addition, the decision whether the utilization of marginal land for biogas production makes environmental sense ultimately depends on the reasons why the land is deemed marginal. “Marginal land” is often used as an umbrella term

for a wide range of different land types including abandoned, degraded and reclaimed land (Dauber et al., 2012). According to Dauber et al. (2012), degraded land is defined by a considerable loss of soil fertility and productivity. On such sites, miscanthus could play a vital role in restoring the soil quality as its cultivation has a positive effect on the composition of soil organic matter (Kahle, Beuch, Boelcke, Leinweber, & Schulten, 2001) and leads to an increase in soil organic content (McCalmont et al., 2017). In addition, it reduces the bulk density and improves the microbial activity and soil porosity (Holland et al., 2015). In summary, it would make sense from an environmental point of view to cultivate miscanthus on land with low soil organic matter content, which is susceptible to erosion or contaminated by heavy metals. This offers the opportunity of restoring the land and at the same time using it for biomass production.

On the other hand, marginal land often harbours a high degree of biodiversity in comparison to intensively used agricultural land (Dauber & Miyake, 2016). Changes in species abundance and loss of habitats through the cultivation of marginal sites for biomass can have negative effects on biodiversity (Dauber et al., 2015; Foley, 2005; Immerzeel, Verweij, van der Hilst, & Faaij, 2014). Miscanthus cultivation could, for example, have a negative impact on bird species typically found on open fields (Bellamy et al., 2009). For this reason, areas with high biodiversity or marginal sites that provide habitats for species worthy of protection should be excluded from biomass cultivation. However, it should be noted that, under certain conditions, miscanthus cultivation has a positive impact on biodiversity, especially when grown in intensive agricultural landscapes (Bellamy et al., 2009; Jørgensen, 2011; Petrovan, Dixie, Yapp, & Wheeler, 2017).

The results of this study clearly show that it can make economic and environmental sense to cultivate miscanthus on marginal land as a substrate for biogas production. The economic sustainability is however limited by the biomass yield. A sharp decline in biomass yield to under 11 t DM/ha can render miscanthus cultivation uneconomic. By contrast, there are no clear thresholds limiting the environmental performance. A decision has to be made on a case-by-case basis, as the environmental sustainability of using marginal land is strongly dependant on site-specific conditions such as soil, topography and local biodiversity.

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