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Greenhouse Gas Mitigation Potential and Mitigation Costs of Biogas Production in Brandenburg, Germany

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This study analyzes the greenhouse gas mitigation potential and corresponding mitigation costs of biogas production in the federal state of Brandenburg, Germany. The production of biogas is based on cattle slurry and maize (*Zea mays L.*) and is used to produce electrical and thermal energy. The impacts of the feedstock and storage facilities chosen, thermal energy use, and land use change on the mitigation potential and the mitigation costs were analyzed by evaluating different scenarios.

In the scenarios analyzed we found greenhouse gas emissions between 0.1 and 0.4 kg CO_2-eq/kWh_{el}, which is 22-75% less than the greenhouse gas emissions caused by the present energy mix in Germany. CO_2-mitigation costs differ between 288 and 1,135€/t CO_2-eq in the scenarios observed. Those costs are influenced by the variability of different substrates, utilization schemes, and the price development of one possible alternative means of production under consideration, namely wheat.

Key words: bioenergy policy, CO_2-mitigation costs, GHG-mitigation potential.

Introduction

The worldwide energy consumption has risen inexorably since the beginning of industrialization in the 19th Century. Against the background of limited fossil energy resources and global warming, the development of pathways to low-carbon energy systems is one of the most challenging tasks of the 21st Century. Embedded within the agreements of the Kyoto Protocol, Germany made the commitment to lower its greenhouse gas (GHG) emissions up to 80%—compared to its 1990 emissions—by 2050. The main instrument needed in order to achieve this ambitious target is the massive expansion of energy production based on renewable resources. The German government recently reconfirmed its commitment to increase the percentage of renewable-resources-produced power in its energy program to 35% for electricity and 14% for heating by 2020 (German Government, 2011). The so called “energy turnaround” should be completed by 2050, with renewable energy accounting for 80% of the total electricity consumption. In order to achieve the expansion of renewable energies, many countries have created regulations or incentives that favor renewable energies, including bioenergy from agricultural resources (International Energy Agency [IEA], 1998; Sims, Hastings, Schlamadinger, Taylor, & Smith, 2006).

Several countries implemented various instruments such as tax exemption, quotas, or direct subsidies to stimulate the use of agricultural resources as renewable energies (Petersen, 2008). In Germany, the Renewable Energy Sources Act, which came into force in 2000, triggered a boom in the use of agricultural resources as feedstock for biogas plants to produce electrical energy (Poeschl, Ward, & Owende, 2010). Since the introduction of the Renewable Energy Sources Act, the number of biogas plants in Germany increased from 1,050 in 2000 to about 5,900 in 2010, with a forecast of 7,000 biogas plants to be operating by the end of 2011(German Biogas Association [GBA], 2011). These will be responsible for about 2% of the power generation and 0.5% of the heat generation in Germany (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2011a). The Renewable Energy Sources Act guarantees producers of electric energy from renewable resources a price higher than the current market price over a period of 20 years, which creates an incentive to produce electric energy from animal manure, energy crops, and other organic material. The anaerobic digestion of organic material and the use of the emerging methane in a combined heat and power unit (CHP) have proven to be a success story in Germany under the economic frame conditions provided with the Renewable Energy Sources Act (Fachagentur Nachwachsende Rohstoffe e.V. [FNR], 2011). The economic costs associated with the development of renewable energies are covered by the consumer and were estimated at 3.53 ct/kWh$_{el}$ for a private German household in 2011 (BMU, 2011b).

Biogas mainly consists of methane (CH_4) and carbon dioxide (CO_2) and may have small amounts of hydrogen (H_2), hydrogen sulphide (H_2S), and ammonia (NH_3). Biogas forms wherever organic material accrues under exclusion of oxygen (anaerobic digestion), e.g., in bogs, on the bottom of lakes, or in ruminants' stomachs. The biochemical process by which biogas forms involves the complex interaction of various microorganisms and takes place in basically four separate phases. Many kinds of organic substrate can be used to produce biogas. In farm-based plants, it is mainly animal excrement that is used as the basic substrate. Other organic materials can also be fermented for biogas to increase the biogas production. In the conducted study, biogas production is based on cattle slurry and maize (*Zea mays L.*).

The dominant energy crop used for biogas production in Germany is maize, which is used as a feedstock for the digestion process—in combination with animal manure or alone—and makes up to more than 75% of the energy crops planted for biogas production (FNR, 2009). The acreage used for biogas production based on energy crops amounted to 650,000 ha in the year 2010, with a forecast of 800,000 ha by the end of 2011, or 7% of the total arable land in Germany (FNR, 2011).

The environmental benefits of using biogas primarily stem from the substitution of fossil energy and the mitigation of emissions which occur in the assumed reference system. Furthermore, biogas plants that use slurry from animal husbandry mitigate emissions from the storage of that slurry (Berg, Brunsch, & Pazcicski, 2006). However, for each impact category, the credits gained from the substitution of fossil energy have to be balanced against the emissions generated during the production and processing of the feedstock.

The Renewable Energy Sources Act leads to high economic costs of biogas use for the production of electrical and thermal energy and the accompanying GHG emission reduction (Scientific Advisory Board on Agricultural Policy [WBA], 2008, 2011; Schaper, Emmann, & Theuvsen, 2011). These costs were mainly caused by governmentally defined and guarantied compensation for electricity and thermal energy fed into the public grid. Recent studies identify CO_2 mititgation costs of energy production, based on biogas combustion used to produce electrical and thermal energy, between 95 and 378€/t CO_2 equivalents (CO_2-eq; Thiering & Bahrs, 2010; Thiering, Empl, & Bahrs, 2011; WBA, 2008, 2011); for biofuels the figures were between 100 and 620€/t CO_2-eq, depending on the observed technology and assumed reference system (De Santi, Edwards, Szekeres, Neuwahl, & Mahieu, 2008; Kalt & Kranzl, 2011; McKinsey & Company, 2009). The literature shows that biomass-based emission-reducing technologies offer a broad range of potential mitigation costs. The presence of alternative technologies with the lower mitigation costs of approximately 20€/t CO_2-eq, such as home insulation programs or energy-saving measures—including practical steps to conserve energy at home and in industry (McKinsey & Company, 2009)—point to the need for a comprehensive analysis of mitigation costs for biomass-based energy generation.

The concept of CO_2 mitigation costs is an effective instrument in determining the economic costs of the governmental support of CO_2-mitigating technologies (IEA, 2009). Comparing different CO_2-mitigating technologies, thus, lower mitigation costs indicate a more efficient instrument of CO_2 reduction. The calculation of CO_2 mitigation costs requires making an estimate of the net GHG mitigation effect along with a cost analysis for the substitution of fossil resources with biogas in order to produce energy and heat. All the processes involved are subject to high uncertainties and assumptions regarding the system boundaries, reference system, and the cost estimates. A comprehensive analysis of the impact of uncertainties of technological coefficients has been provided by Meyer-Aurich et al. (2012). They found a huge variance of the GHG mitigation potential of biogas use based primarily on uncertainties of the fate of nitrogen in the process, which may cause GHG-relevant N_2O emissions. Furthermore, the feedstock used, process engineering, and land-use change issues determine the GHG mitigation potential of biogas to a great extent. However, an economic analysis of the impact of the main processes and assumptions determining the CO_2 mitigation and corresponding CO_2 mitigation costs is lacking. Therefore, the aim of this article is to provide a comprehensive analysis of the GHG mitigation potential and mitigation costs of biogas use for the production of electrical and thermal energy, taking into account different production processes, land-use scenarios, and production alternatives. The calculations were conducted for a constructed farm model representing a typical farm with dairy and cereal production in Brandenburg (northeastern Germany). The article builds on a research study on the GHG mitigation potential of biogas from agricultural resources by Meyer-Aurich et al. (2012) and focuses on the discussion of the economic

Table 1. Scenarios.

Scenario	Feedstock	Thermal use	Digestate storage	Land use change
I	Cattle slurry & silage maize	No additional thermal use	Gas tight	-
II (thermal use)	Cattle slurry & silage maize	Additional thermal use	Gas tight	-
III (open storage)	Cattle slurry & silage maize	No additional thermal use	Open storage	-
IV (maize as sole feedstock)	Silage maize	No additional thermal use	Gas tight	-
V (land-use change [LUC])	Cattle slurry & silage maize	No additional thermal use	Gas tight	25 % induced LUC
VI (maize + LUC)	Silage maize	No additional thermal use	Gas tight	25 % induced LUC

Source: Own calculations

costs of CO_2 reduction with different biogas production systems.

Data and Methods

Farm Model and Biogas System

GHG mitigation potentials and mitigation costs were calculated for a constructed farm model, representing a typical farm with dairy and cereal production in Brandenburg (northeastern Germany), which served as the reference scenario. To simulate the effect of integrating a biogas plant into an agricultural farm, we compared the GHG emissions of a reference system without a biogas production facility with six biogas-using scenarios (Table 1), which will be explained below.

In the reference system, we assumed an open storage facility for the animal slurry, which had a naturally-formed surface crust. N_2O and CH_4 emissions during storage were estimated according to Intergovernmental Panel on Climate Change (IPCC) methodology. Details of the methodology for the estimation of greenhouse gases are documented in Meyer-Aurich et al. (2012). In the biogas systems using cattle slurry (Scenarios I, II, III, and V), emissions from the cattle slurry storage were assumed to be avoided, since the slurry would be pumped into the digester, which captured all gaseous emissions.

The standard scenario (Scenario I) assumed a gas-tight storage tank to prevent gaseous emissions from the digestate from escaping. The tank met the current regulations for new biogas plants in Germany. The produced biogas was converted into electrical energy in a CHP and then fed into the public grid. We assumed that the produced electric energy from biogas combustion substitutes for fossil energy, based on the present energy mix in Germany. For all the biogas production systems, we assumed a typical farm-based biogas plant in Germany with an installed electrical capacity of 500 kW, producing the electrical energy equivalent to 8,200 hours at full-load operating time per year. The biogas plant was supposed to be operated under mesophilic conditions (38°C) with a fermenter, equipped with a completely stirred digester and a post-digester, which was designed to capture all CH_4 from the digestate.

Thermal energy, as a side-product of the combustion process, is used to heat the digester in order to maintain the anaerobic process. Another use of the heat has been considered in Scenario II, where an additional credit for thermal use (230,000 kg CO_2-eq) was accounted for following Vogt (2008) and was assumed to substitute thermal energy based on natural gas combustion. To simulate the effect of different digestate handlings, we included a scenario (Scenario III) with an open storage tank, as this still is the current practice of 50% of biogas farmers in Germany (FNR, 2009). Two scenarios (Scenarios IV and VI) were included with only maize as feedstock (monofermentation) in order to analyze the impact of the particular feedstock chosen on GHG emissions. All necessary inputs, which were needed for the estimation of the GHG emissions due to maize production, were taken from Hanff, Neubert, and Brudel (2008). Land-use change (LUC) was considered in two scenarios (V and VI), where we assumed a 25% LUC scenario, meaning that 25% of the acreage needed for maize production was realized on fields which were formerly used as grasslands.

In the reference system, only the slurry would be distributed to the arable fields. In the biogas system, the digested slurry together with the digested energy crops were assumed to be spread over the fields. In the monofermentation scenarios observed (Scenarios IV and VI), the digestate consisted only of the residues of the maize, whereas in the assumed cofermentation scenarios (Scenarios I, II, III, and V) the digestate also consisted of cattle slurry residues. For the economic analysis, only the additional digestate from the maize was considered, since the cattle slurry also was used in the reference system. The nutrients contained in the energy crop digestate substituted for mineral fertilizer. This was accounted for with respect to losses and the amounts of the nutrients available to the plants. The substitution of mineral fertilizer by the energy crop digestate was also considered in the calculations of the maize production costs. The calculations were based on a maize yield of 11 t/ha with 10% mass losses due to the silage.

Estimation of GHG Emissions

To estimate mitigation potentials of biogas production, GHG emissions due to the production of biogas were compared with a reference situation as described above. This was done according to life-cycle assessment standards following Cherubini (2010). Gaseous emissions such as CO_2, CH_4, and N_2O were taken into account according to their global warming potential (GWP) over a 100-year time span (Solomon et al., 2007). The GWP is expressed in CO_2 equivalents (CO_2-eq).

All emissions attributable to the production of the biogas facility, including possible methane losses and the manufacturing of the CHP unit, were taken into account and allocated to one production year (according to the useful life of the implements). Within the biogas process, fugitive losses of methane are highly variable. Following IPCC methodology (Eggleston, Buendia, Miwa, Ngara, & Tanabe, 2006) these losses range from 0 to 10% of the produced methane. Considering the latest studies and applying the current standard for biogas plants, we assumed for the biogas model fugitive methane losses of 1% of the produced methane, including leakage and CHP slip (Meyer-Aurich et al., 2012). All emissions attributable to the energy-crop production—including the input of seeds, machinery, fuel, fertilizer, and pesticides as well as the manufacturing of these inputs—were taken into account. More details on the calculation of the GHG emissions can be found in Meyer-Aurich et al. (2012).

The amount of CO_2 released due to the effects of LUC may vary substantially as a function of the initial carbon content (Heinemeyer & Gensior, 2004). Typically, CO_2 emissions in the first years after the conversion are higher until the soil carbon reaches a new equilibrium (after decades). We assumed 2.6 t CO_2 emissions per year due to LUC, based on the calculations of Fritsche and Wiegmann (2008).

Economic Analysis

An economic analysis was conducted in order to estimate the CO_2 mitigation costs of the biogas use for electrical and thermal energy production. The CO_2 mitigation costs (MC) were calculated according to IEA (2009).

$$MC = \frac{C_i - C_{ref}}{E_{ref} - E_i}, \tag{1}$$

where C_i denotes the production costs of the alternative technology (€/kWh_{el}), C_{ref} denotes the production costs of the reference technology (€/kWh_{el}), E_i represents the emissions resulting from the energy generation of the alternative technology observed (kg CO_2-eq/kWh_{el}), and E_{ref} denotes the emissions resulting from the energy-generation of the reference technology observed (kg CO_2-eq/kWh_{el}).

Equation 1 shows that the estimations of the production costs of the alternative technology are essential for the calculation of the economic costs of CO_2 reduction, which is based on the production of energy by the combustion of biogas. The production costs of the alternative technology (i.e., the use of biogas for electrical and thermal energy production) were calculated following standard accounting rules and financial mathematic fundamentals according to KTBL (2009). The costs of biogas production (€/kWh_{el}) include capital costs, operating costs of the biogas plant, and feedstock costs with respect to opportunity costs for land use. The economic impact of substituting mineral fertilization in the form of the digestate from the biogas plant on the cost of maize was considered. All the processes involved in the production chain of maize were accounted for following Hanff et al. (2008). The costs of biogas production (€/kWh_{el}) were mainly influenced by the production costs of the feedstock maize. Approximately 48% of the total production costs (€/kWh_{el}) were caused by the production of maize. These figures rose to 55% of the total production costs in the monofermentation scenarios observed. These facts were caused by a higher demand for maize to generate the target capacity of the CHP (500 kW) due to the absence of the feedstock cattle slurry. The total production costs of the biogas production, without opportunity costs for land use, were calculated between 18 and 20 ct/kWh_{el} in the scenarios observed, which reflected the then current average production costs of biogas plants in Brandenburg (FNR, 2009). For the reference technology (present energy mix in Germany), we assumed production costs of 4 ct/kWh_{el} according to Zybell and Wagner (2006) and emissions of 0.611kg CO_2-eq/kWh_{el}, according to Vogt (2008).

All the scenarios analyzed used maize as a feedstock for the biogas production. Since the cattle slurry also occurred in the reference system, no further costs were accounted. The feedstock costs of maize were based on

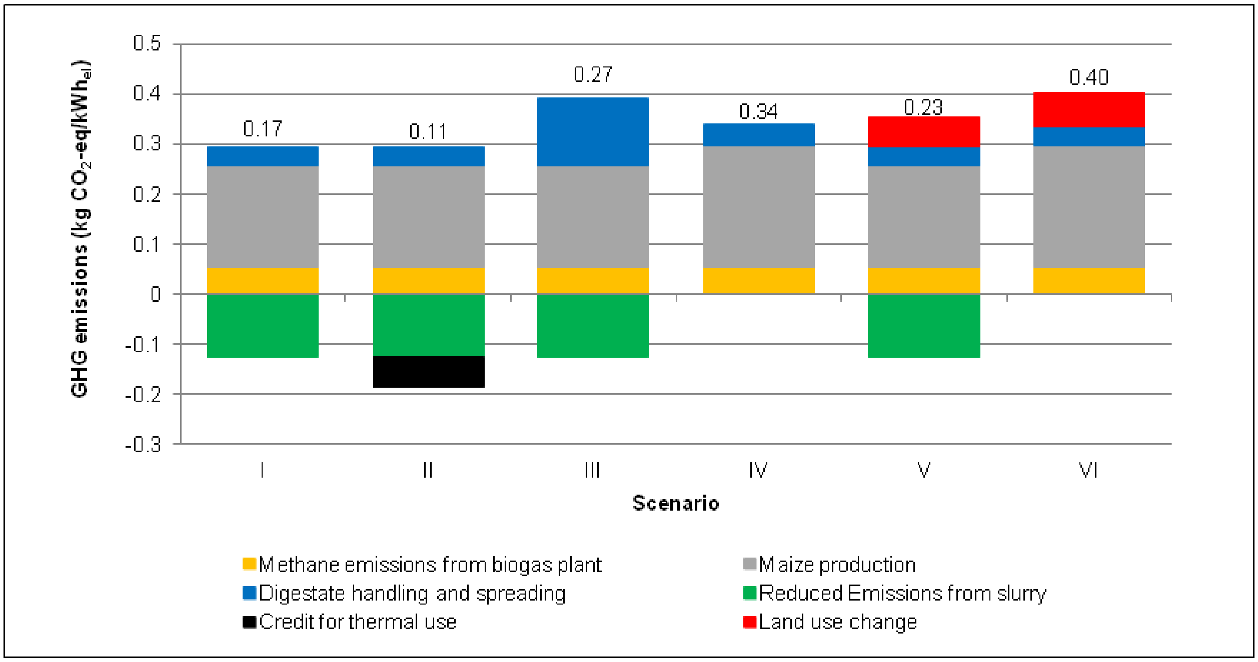

Figure 1. GHG emissions of the observed scenarios.

Source: Meyer-Aurich et al. (2012)

the production costs and the opportunity costs of an alternative production possibility (wheat). The feedstock costs of maize (FC_M) were calculated according to Equation 2.

$$FC_M = \frac{PC_M + OC_W}{Y_M}, \tag{2}$$

where PC_M represents the production costs of maize, whereas OC_W indicates the opportunity costs of wheat and Y_M is the yield of maize. We assumed 1,088€/ha for the production costs of maize, according to Hanff et al. (2008). The feedstock costs of maize vary between 36 and 69€/t dry matter (DM) as a function of the opportunity cost of wheat. The opportunity-cost approach allows for making a statement in order to define the impacts of a no-longer realizable production alternative on economic costs of biogas production. These opportunity costs represent the cost of land as a production factor for the production of maize in the biogas systems.

The opportunity costs of wheat depend on the production costs of that grain and its assumed price, according to Hanff et al. (2008). We analyzed the impact of the price of wheat on the CO_2 mitigation costs in a range from 95 to 250€/t. This broad range reflects the current volatile price development on world wheat markets. A wheat price of 95€/t covers the production costs and is therefore the break-even price of the wheat production system. Every rise in the price of wheat would generate a potential benefit for the farmer. In the biogas system, this benefit is represented by the opportunity costs of the alternative production possibility—in this case wheat—and therefore indicates the cost of land as a production factor in the biogas systems observed.

Results and Discussion

GHG Emissions of Biogas Production

In all scenarios considered, the GHG emissions due to biogas production were lower than the emissions in the reference system. The net GHG emissions vary between 0.11 and 0.4 kg CO-eq/kWh$_{el}$ (Figure 1), while the GHG emissions of the reference system (energy mix Germany) result in 0.611 kg CO_2-eq/kWh$_{el}$. The great range of GHG emissions due to the production of biogas illustrates the relevance of feedstock and technology selection, as well as assumptions on the effect of land-use change, which determine the range of the values calculated for the scenarios. The results are within the range of a study by Graebig, Bringezu, and Fenner (2010), with 0.17 kg CO_2-eq/kWh$_{el}$, but are much higher than the specific emissions found by Gerin, Vliegen, and Jossart (2008), which were between 0.003 and 0.104 CO_2-eq/kWh$_{el}$. It needs to be noted that the GHG emissions calculated by Gerin et al. (2008) do not

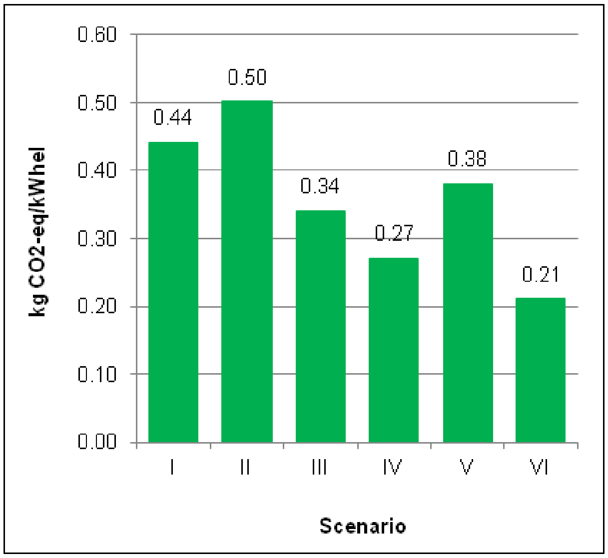

Figure 2. GHG mitigation potential of the observed scenarios.
Source: Meyer-Aurich et al. (2012)

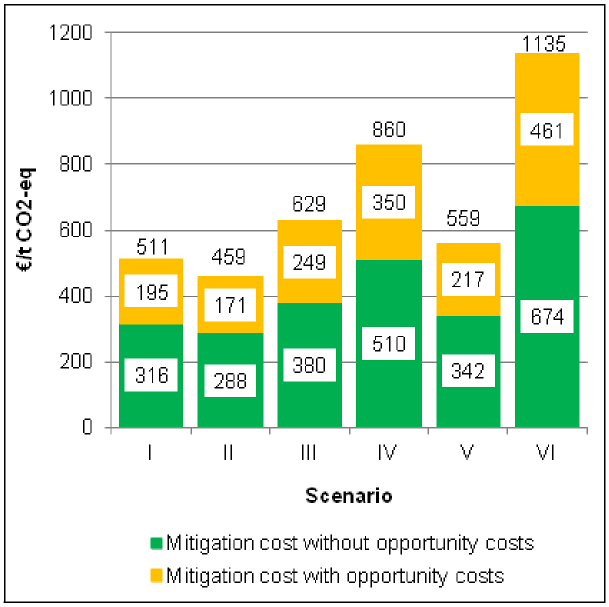

Figure 3. CO_2-mitigation costs of the observed scenarios.
Source: Own calculations

include N_2O emissions and the pre-chain emissions, due to the use of nitrogen fertilizer. Given that these emissions contribute more than 50% of the emissions of maize production (Meyer-Aurich et al., 2012), the higher emission values of our calculations are plausible. In all scenarios, the emissions due to maize production have the greatest contribution. The second biggest contribution to the GHG emissions in the open-storage scenario (Scenario III) was the digestate handling and spreading. In the other scenarios, this source of emission was lower than methane emissions from the biogas plant and the LUC-induced emissions. The credits for reduced emissions from cattle slurry only applied if the cattle slurry was used as a feedstock (Scenarios I, II, II, and V). These credits were higher than the additional credits for thermal use (Scenario II). The difference between the emissions of the reference system and the biogas scenario is the GHG mitigation potential of the latter, varying accordingly between 0.21 and 0.5 kg CO_2-eq/ kWh_{el} (Figure 2). The highest mitigation potential is realized with Scenario II, where biogas production is based on cattle slurry and maize in order to produce electricity and heat. The lowest mitigation potential was calculated for Scenario VI, where the effects of monofermentation of maize and LUC (covering 25% of the acreage of the maize production) were assumed. Note that the GHG mitigation potential of maize as the sole feedstock drastically reduces with the increased effects caused by land-use change. The effects of LUC extended to100% of the maize fields would leave the GHG mitigation potential of maize at close to zero (data not shown).

CO_2 Mitigation Costs

The CO_2 mitigation costs were calculated based on the determined GHG mitigation potentials and the costs associated with the biogas production in the different scenarios (Figure 3). The figure shows the mitigation costs due to biogas production. It also shows possible opportunity costs for land use with wheat prices between 95 and 250€/t in cases in which the land can be used to produce wheat. No opportunity costs occurred with an assumed wheat price of 95€/t or below. In this case, the alternative production possibility would generate no economic benefit and appears to be cost-effective only when the wheat price is at 95€/t. With higher wheat prices, the production alternative would generate an economic benefit for the farmer, namely the opportunity cost of using the land for bioenergy production. Across the scenarios considered, the mitigation costs vary between 288 and 674€/t CO_2-eq without opportunity costs for land use. Compared to studies from De Santi et al. (2008), McKinsey and Company (2009), WBA (2011), Kalt and Kranzl (2011), and Thiering et al. (2011), our results are located at the higher end of the quoted results or even above. Comparatively higher results in the present case are justified by different aspects, which will be discussed below. The assumed reference and biogas systems were set up to accommodate the situation in the federal state of Brandenburg, located in northeastern Germany. The yield potential of maize in this agricultural zone is lower compared to other regions in Germany or Europe, implying higher GHG emissions per ha and higher production costs.

In this study, higher yields of maize per ha would lead to direct implications on the acreage needed for the cultivation of maize. A reduced demand for land would lower the costs and emissions of maize production. This would imply lower costs of biogas production and therewith lower CO_2 mitigation costs. It should be noted that the calculated CO_2 mitigation costs derived from this study are not directly transferable to a global scale and it appears that regional CO_2 mitigation costs, due to different yield expectations, may differ significantly. Nevertheless, our calculations give a good estimate on the economic costs of biomass-based CO_2-reducing systems in agricultural zones with low yield expectations.

Taking opportunity costs for land into account, the CO_2 mitigation costs nearly double to 459-1,135€/t CO_2. Opportunity costs for land applies if the economic returns of other land use are higher than bioenergy via maize production, which is subject to crop prices. The reference crop with the highest net return for the considered production system is winter wheat. Hence, the wheat price determines the opportunity costs for land. The opportunity costs are higher when maize is used as the sole feedstock since more maize needs to be planted to produce the same amount of electrical energy. Furthermore, the CO_2 mitigation potentials determine the opportunity costs in the scenarios. Lower mitigation potentials per kWh imply higher susceptibility to opportunity costs for land.

The lowest mitigation costs were associated with Scenario II, where maize and slurry is used for the integrated production of electrical and thermal energy through the combustion of biogas. The highest mitigation costs were caused by Scenario VI, where biogas is produced solely by maize, the accrued thermal energy is not used for energy needs, and LUC on 25% of the maize acreage was assumed. High mitigation costs, between 510 and 1,135€/t CO_2-eq within the monofermentation scenarios, are mainly caused by higher emissions due to the additional maize production (Figure 1) and higher costs of biogas production due to the absence of the feedstock cattle slurry and a therefore associated higher demand in cultivated land. The results derived by a study of Thiering et al. (2011), where they calculated CO_2 mitigation costs of approximately 100€/t CO_2-eq for biogas systems that use cattle slurry as their sole feedstock, support our findings and showed the advantages of animal-excrement-based biogas systems in regard to an economically efficient CO_2-reduction instrument.

The lowest impact of opportunity costs on CO_2 mitigation costs was derived from Scenario II. A marginal rise in price of wheat by 1€ causes an increase in CO_2 mitigation costs of about 10€/t CO_2-eq. The highest impact of opportunity cost on CO_2 mitigation costs was calculated for Scenarios IV and VI. Thereby a marginal increase in the price of wheat by 1€ leads to an increase of CO_2 mitigation costs of about 18€/t CO_2-eq in Scenario IV and 24€/t CO_2-eq in Scenario VI. The higher impact of the opportunity costs on the mitigation costs in the monofermentation scenarios observed (Scenarios IV and VI) can be explained in different ways. We chose the opportunity cost approach in order to indicate the cost of required land for the production of the feedstock maize. The higher requirement for land, due to the absence of the substrate cattle slurry within the monofermentation scenarios, to produce the same amount of energy compared to the cofermentation scenarios (Scenario I, II, III, and V), explains the higher impact of opportunity costs on mitigation costs to some extent. In fact, lower mitigation potentials (0.27 kg CO_2-eq/kWh_{el} for Scenario IV and 0.21 kg CO_2-eq/kWh_{el} for Scenario VI) of the monofermentation scenarios contribute to a higher impact of opportunity costs on mitigation costs as well. Comparing the three cofermentation scenarios without LUC (I, II, and III), in regard to their mitigation potential and the impact of opportunity costs on the mitigation costs, underlines this finding.

In addition to the great range of the mitigation potentials of biogas, the range of mitigation costs of different scenarios increases with different prices for wheat as an alternative production option. Furthermore, assumptions about the reference system (i.e., the electrical energy which is substituted) dramatically affect mitigation costs of the biogas systems studied. There is an ongoing discussion as to whether the marginal or the average energy mix is relevant for the analysis of the mitigation of renewable energy, which in turn strongly affects the mitigation potential and the mitigation costs (Klobasa, Sensfuß, & Ragwitz, 2009).

Cherubini (2010) suggests using the best available fossil technology as a reference. Applied to this study, this would imply the use of natural gas, which would dramatically reduce the mitigation potential of biogas and further increase the mitigation costs.

Conclusions

The study showed that the production of biogas from agricultural resources as an energy source for electrical and thermal energy may contribute to the mitigation of GHG emissions by offsetting emissions from fossil resources and by reducing emissions from the storage of animal slurry. The costs for the mitigation of CO_2 are very high, though. The calculated CO_2 mitigation costs differed between 288 and 674€/t CO_2-eq. The integration of electrical and thermal energy production and the usage of animal slurry for energy purposes (Scenario II) lowered the CO_2 mitigation costs compared with the monofermentation scenarios that we observed. Therefore, the integration of electrical and thermal energy production and the usage of animal slurry, for energy-producing purposes, appeared to be useful for GHG emissions reduction. The governmental support of biogas systems, which mainly concentrate on the biogas production based on the feedstock maize, appeared to be economically inefficient, if CO_2-emission reduction is the overall target. Taking the cost of land use into account, when calculating the feedstock costs of maize, this fact becomes even more evident: the CO_2 mitigation costs rose between 10 and 24€/t CO_2-eq in the observed scenarios with every increase of wheat prices by 1€/t to 454-1,153€/t CO_2-eq. Despite the high CO_2 mitigation costs, the production of electrical energy with biogas from agricultural resources is economically attractive for farmers because of the regulations of the Renewable Energy Sources Act in Germany. Even though biogas is a multi-talent in terms of possible usage applications (electricity, heat, fuel), biogas systems that focus mainly on maize-based biogas production appear to be not economically efficient in CO_2 reduction. A promising economically efficient biogas system for CO_2 reduction appears to focus on animal-excrement-based biogas production.

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