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Comparison of the environmental effects of manure- and crop-based agricultural biogas plants using life cycle analysis

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ABSTRACT

The environmental effects of anaerobic digestion (AD) plants have not, to date, been thoroughly analysed. The technology of biogas production has developed enormously in the last 10 years, with equipment functioning at ever-improving efficiency. In the present study, we aimed to examine the environmental effects of biogas plants that operate with the same power production capacity, but use different raw materials during the full life cycle. In addition, the environmental effects that occur during the establishment of AD plants were defined and contrasted against emissions during the full life cycle. In life cycle analysis (LCA), the greenhouse gas (GHG) emission effect of biogas production was measured as kg CO_2 eq/kWh$_e$, the acidification potential as kg SO_2 eq/kWh$_e$, and the eutrophication potential as kg PO_4 eq/kWh$_e$. The calculations proved that an AD plant that processes only energy crops as raw materials can be regarded as a CO_2 absorber (−188 g/kWh$_e$). The CO_2 emission of all three examined plants was below the average emission of electrical power currently produced in a conventional manner. The AD plant that processes low-energy-density agricultural wastes produced 7.7% of its full-life-cycle CO_2 emissions during its construction phase, compared with a 0.9% ratio for the AD plant processing only energy crops. However, the manure-based AD plant contributed the most to the decline in environmental acidification.

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1. Introduction

In Germany in 2012, the number of anaerobic digestion (AD) plants that process agricultural raw materials increased to 7874. During the same period, their installed power output was 3384 MW$_{el}$ (Fachverband Biogas e.V.) and their total gross electricity production was 27,239 GWh/a (EUROBSERV'ER, 2014). These translate into 0.43 MW$_{el}$/AD unit and 3.46 GWh/AD unit per year, respectively. Meanwhile, in the United Kingdom (UK), the second largest European Union (EU) biogas market, primary energy production from biogas was based mainly on landfill gas and sewage sludge gas (EUROBSERV'ER, 2012). The number of farm-scale biogas plants in the UK reached 78 in 2012 (Committee on Climate Change, 2013), with an installed electrical capacity of 110 MW (Department of Energy and Climate Change, 2014). In the USA, the number of farm-scale biogas plants was 193, with an installed electrical capacity of 160.1 MW; however, only 3% of these AD plants used co-fermentation; the rest were based on manure from animal husbandry (AgSTAR | US EPA, 2014). The country specific biogas production patterns are depicted in Table 1 below.

These numbers show that other countries undoubtedly lag behind Germany in biogas production. Nonetheless, it is worth noting that the majority of German AD plants produce biogas from arable-land-based biomass, primarily maize silage. The by-products of animal husbandry are only partially used for power generation. As a comparison, energy crops used as raw materials for biogas plants were cultivated on 800,000 ha out of 11.874 million hectares of agricultural land in Germany (Statistisches Bundesamt, 2013). To manage valuable trade-offs that are worth paying, it is necessary to supply policy developers with accurate numbers with regard to environmental performance for these technologies.

When potential environmental policy goals are set to increase the renewable energy production on the basis of AD plants, possible raw material sources and utilisation chains must be examined, i.e. energy crop cultivation or waste recycling. The potential environmental effects should also be considered, and the direction of further development determined on the basis of accurately

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Table 1
Main characteristics of biogas production in different countries.

	Germany	United Kingdom	United States of America
Country size (km^2)	357,021	243,610	9,826,675
Number of biogas plants using agricultural raw materials	7874	78	193
Total installed capacity (MW_{el})	3384.0	110.0	160.1
Specific capacity (MW_{el}/AD unit)	0.430	1.410	0.823
Specific produced electricity (GWh/AD unit·year)	3.46	6.71	4.36

calculated figures. Previous studies (Berglund, 2006; Finnveden et al., 2005; Jury et al., 2010; Poeschl et al., 2010, 2012; Scholwin, 2006) neglected the GHG emissions related to the construction of an AD plant during the full life cycle (assumed to be less than 1%, which is possible in some cases). Several calculations have been made to compare the CO_2 emissions of biogas plants, and these indicated a positive CO_2 balance (Bacenetti et al., 2013; Bachmaier et al., 2010; Bachmaier, 2012; Bohn et al., 2007; Börjesson and Berglund, 2006; Jury et al., 2010; Scholwin, 2006) when producing 1 kWh electricity; however, these values have not been compared with other environmental parameters, such as acidification or eutrophication. The centralised or distributed infrastructure of AD plants has already been investigated (Berglund, 2006; Patterson et al., 2011; Poeschl et al., 2010) and showed marginal extra-environmental effects if the substrates were transported over longer distances. Thus, the positive economic effects of scale-up with bigger fermentation capacities can be realised while keeping environmental burdens low.

The present study aimed to examine the environmental burden of high-tech industrialised, but farm-scale AD plants, and the effect of utilising various agricultural raw materials on the environmental performance of the examined biogas plants. To analyse the environmental effects of possible substrate usage strategies in agriculture, detailed data on the erection and operation of three AD plants were collected and analysed.

2. Methodology

To achieve the previously set goal, LCA, based on the EN ISO 14044:2006 standard (International Organization for Standardization, 2006), was performed with the GaBi 6 life cycle analysis software (PE International AG) using the Ecoinvent 2.2 database (Swiss Centre for Life Cycle Inventories, 2010) accompanied by desk research and data collected on-site.

2.1. Function and functional unit

EN ISO 14044:2006 requires the definition of the product system and the functional unit of LCA. In the present study, the product system inspected was AD of energy crops and/or agricultural wastes from animal husbandry in small-scale decentralised AD plants. The generated biogas was used in a cogeneration unit to produce heat and electricity.

Here, the end product of the examined process, using a cradle-to-gate approach, is the electricity exported (kWh) into the grid. It is also its functional unit (FU), to which all the relevant environmental effects are referred.

2.2. System boundary and allocation procedure

The first step to define the life cycle's environmental effects was to determine the life cycle's boundaries as depicted in Fig. 1 and its time span (International Organization for Standardization, 2006; Klöpffer and Grahl, 2009). In this case, a 'cradle-to-gate' life cycle was analysed, just as in many recent studies (Bacenetti et al., 2013; Lijó et al., 2014b); this means that all of the materials and energy flows necessary for the establishment and operation of the AD plant, and the land use requirement, were considered with all their upstream material and energy flows up to the produced energy unit. Therefore, the system boundary of the examined life cycle starts with the construction of the AD plant comprising up-flows of all materials and energy inputs during the operation and includes the cultivation of necessary feedstock. The process ends when biogas is transformed to electricity (FU) at the gas engine generator.

The input side of the inspected product system has construction-related and feedstock-related input flows. Among these flows, construction flows and energy-crop-based feedstock are considered with their full up-flow streams, according to the cradle-to-gate approach. The 'gate-to-gate' life cycle was only considered with animal-husbandry-based feedstock, such as manure and slurry, because here only direct manure emissions were calculated for the AD plant, whereas upstream flows, such as material and energy flows of animal breeding and its necessary crop cultivation, were not. This is because these environmental effects are mainly due to primary products, such as meat or milk, and only partially burden side products or wastes, such as manure and slurry. This corresponds to the allocation procedure of the Ecoinvent 2.2 AD LCA descriptions (Jungbluth et al., 2007). Most biogas LCA studies entirely neglect these whole upstream flows of manure (Bachmaier et al., 2010; Bachmaier, 2012; Berglund, 2006) or use a replacement approach (Bacenetti et al., 2013; Lijó et al., 2014b). However, because some elementary flows (mainly emissions from temporary storage and manipulation) of manure emerge during the utilisation process, we decided to consider them. Transport expenditures of the substrate, if not generated on site, were taken into account as environmental burdens.

To make comparisons possible, the observed AD plants were selected such that the produced biogas quantity could be the same every year, i.e. the fermentation size of plants was adjusted to the produced electricity on a yearly basis. Thus, all the examined biogas plants were designed with an identical electricity power capacity (600 kW). However, the AD plants operated on different agricultural raw-material flows. The life span of an AD plant was determined to be 20 years, and other equipment, such as pumps, stirrers, solid material feeding systems, and combined heat and power (CHP) with a shorter life span, were consequently considered. This equipment was accounted for at least twice in the life cycle inventory analyses to model the necessary replacements.

2.3. Life cycle inventory analyses

As a next step, the list of material and energy flows entering and leaving the life cycle was compiled. This is life cycle inventory analysis (LCI), which contains all the material and energy flows with an environmental effect, either absorbed from the environment or injected into it. These are the so-called elementary flows. In Fig. 1, the elementary flows are indicated by the exiting arrows from the field of production on both the input and output sides. The material and energy flows inside the system serve only as system element interconnections, also known as tracked flows (Frischknecht and Jungbluth, 2007; Klöpffer and Grahl, 2009; Sára, 2010).

In the present study, three types of AD plant were examined. Their structures and characteristics are summarised in Table 2.

The three plants were as follows.

1. ADP1: Exclusively crop-based biogas production.
2. ADP2: Crop-, slurry- and manure-based biogas production.

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