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Comparative life cycle assessment of biogas plant configurations for a demand oriented biogas supply for flexible power generation

Henning Hahn [a,*], Kilian Hartmann [b], Lutz Bühle [c], Michael Wachendorf [c]

[a] Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Division Bioenergy System Technology, Königstor 59, D-34119 Kassel, Germany
[b] Department of Engineering Science, University of Applied Sciences Aschaffenburg, Würzburger Str. 45, D-63743 Aschaffenburg, Germany
[c] Department of Grassland Science and Renewable Plant Resources, University of Kassel, Steinstr. 19, D-37213 Witzenhausen, Germany

HIGHLIGHTS

- Life cycle assessment of biogas plant configurations for flexible power generation.
- Environmental effects of biogas plants producing biogas on demand.
- Comparison of biogas storage and flexible biogas production concepts.
- Processing PF from bio waste increases GHG savings and agricultural biodiversity.
- Methane emissions can be reduced by thicker biogas storage membranes.

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ABSTRACT

The environmental performance of biogas plant configurations for a demand – oriented biogas supply for flexible power generation is comparatively assessed in this study. Those configurations indicate an increased energy demand to operate the operational enhancements compared to conventional biogas plants supplying biogas for baseload power generation. However, findings show that in contrast to an alternative supply of power generators with natural gas, biogas supplied on demand by adapted biogas plant configurations saves greenhouse gas emissions by 54–65 g $CO_{2\text{-eq}}$ MJ^{-1} and primary energy by about 1.17 MJ MJ^{-1}. In this regard, configurations with flexible biogas production profit from reduced biogas storage requirements and achieve higher savings compared to configurations with continuous biogas production. Using thicker biogas storage sheeting material reduces the methane permeability of up to 6 m^3 d^{-1} which equals a reduction of 8% of the configuration's total methane emissions.

1. Introduction

Global warming is an imminent environmental issue the world is facing today. There is a consensus among scientists that climate change is caused by large scale anthropogenic emission of greenhouse gases (GHGs), which in relevant parts are caused by the combustion of fossil fuels for energy generation (Cook et al., 2013). In order to mitigate climate change, the European Union has committed to reducing GHG emissions to 80–95% below the level of the 1990s by the year 2050 (according to European Commission). For energy – related CO_2 emissions alone, meeting this goal requires a reduction of approximately 85%, ultimately aiming for a power supply that is almost emission-free. Renewable technologies are considered as clean sources and optimal use of these sources will mitigate energy-related GHG emissions (Panwar et al., 2011).

Since water and biomass are limited resources, the largest contributions to RE systems will have to come from wind and solar power (Hinrichs-Rahlwes, 2013). Nevertheless, high proportions of fluctuating RE will present a number of challenges, especially regarding the need to balance the variable energy demand with the weather dependent fluctuation of energy supply. Technologies

Abbreviations: BS, biogas storage; CHP, combined heat and power generation; CP, conventional biogas plant; CP-BS, CP expanded by an external biogas storage; CP-BS-IFBB, CP-BS expanded by the IFBB technology; CP-UI, CP expanded by an biogas upgrading and biomethane injection system; DM, dry matter; EPDM, ethylene–propylene–diene monomer; FBPC, flexible biogas production configuration; FBPC-IFBB, FBPC expanded by the IFBB technology; FM, fresh matter; GHG, greenhouse gas; ha, hectare; HHV, higher heating value; IFBB, integrated generation of solid fuel and biogas from biomass; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle analysis; LHV, lower heating value; PF, press fluid; RE, renewable energy; SOC, soil organic carbon; th., thermal; VDLUFA, Association of German Agricultural Investigation and Research Institutions; Vol, volume.

* Corresponding author. Tel.: +49 561 7294 261; fax: +49 561 7294 260.
E-mail address: Henning.Hahn@iwes.fraunhofer.de (H. Hahn).

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with high ramp rate capabilities, such as gas fired power plants, energy storage, demand-side management, power imports and exports with neighboring countries and the extension of the electricity transmission grid will be needed to cope with the increasing volatile residual load (electrical demand minus power generated through fluctuating RE sources). In this context, energy from biogas or biomethane offers the advantage of high availability and high predictability. Biomass input substrates or biogas can be stored and electricity can be generated on demand, in order to help balancing the fluctuating power generation from weather-driven RE.

In contrast to base load operation mode, flexible power generation based on biogas principally requires excess power capacities which can easily be extended by additional or larger generators. However, it is more challenging to guarantee the availability of biogas (biomethane) whenever it is needed for power generation, especially if periods of several days without any biogas demand need to be balanced. This can generally be realized by biogas storing or flexible biogas production concepts, which are comprehensively analyzed and reviewed by Hahn et al. (2014a). Both concepts are economically assessed considering their additional flexibility costs by Hahn et al. (2014b). Revenues of biogas plants with excess power generators in electricity spot markets and ancillary service markets are investigated by Hochloff and Braun (2014).

Various environmental impact analyses conducted in recent years have shown that in comparison to the use of fossil fuels, using biogas or biomethane for power generation leads to reduced greenhouse gas emissions. Most of them have assessed the sustainability of biogas production for baseload electricity generation. In this regard, the environmental impact of different substrate types and biogas plant sizes has been investigated (Borjesson and Berglund, 2007; Hartmann, 2006). Other studies have compared the environmental performance of biomethane production and injection into the national grid with imported natural gas (Jury et al., 2010). However, until today no study has analyzed biogas plant configurations which are adapted to variable biogas (resp. biomethane) demand for flexible power generation. These configurations including their balancing capabilities will become more important with increasing proportions of fluctuating RE in energy supply systems. Hence, this study aims to assess the energy and environmental performance of biogas plant configurations which are able to stop the biogas (resp. biomethane) supply and consequently the power generation over a period of three days. During this period, biogas can be stored and/or its production can be decreased. This represents typical situations of several days with low prices for electricity such as on weekends (until Monday morning) and during time periods with very high amounts of electricity generation from solar and wind energy.

The study is conducted according to the principles of life cycle assessment (LCA), considering the impact categories of primary energy and greenhouse gas balance as well as acidification and eutrophication balance. The results of the LCA are related to the impact of supplying the power generator with natural gas. Furthermore, the effect of varying biogas storage sheeting thickness is investigated, since all configurations require enlarged biogas storage volumes to ensure the biogas supply for flexible power generation. In this regard, the study addresses the following questions:

(i) How big is the environmental impact of the necessary additional primary energy and CO_2-input to adapt biogas plant configurations to the variable biogas demand for flexible power generation and do they, in comparison to a natural gas supply, manage to save GHG emissions and primary energy?
(ii) Do configurations based on flexible biogas production or biogas storage concepts perform better regarding their primary energy and GHG balance?
(iii) How does the addition of press fluid from grass silage influence the configuration's environmental performance?
(iv) What effect does a varying thickness of biogas storage membranes have on the configuration's GHG emissions?

2. Methods

2.1. Functional unit and system boundaries

The functional unit is 1 MJ biogas (resp. biomethane, related to the lower heating value (LHV)) supplied to the power generator for flexible power generation. As an energy-related unit, MJ allows comparing the performance of the different biogas plant configurations with each other, as well as with alternative fossil fuels.

The production system includes biomass cultivation and supply, biogas production and storage, as well as, if applied, biogas being converted into biomethane and biomethane grid injection with transportation via the natural gas grid to the power generation system. The power generator is excluded by the system boundaries, as the focus is, for this approach, to assess the performance of biogas plant configurations, which are able to supply biogas on demand for flexible power generation. Investigations which include the power generator are very site-specific and should consider the individual framework conditions, such as the heat consumer requirements as well as the proportions of electricity which may be sold on different electricity markets. The requirements for the demand-oriented biogas supply for flexible power generation in this study are defined by the ability of all configurations to balance three days without biogas consumption.

All assessed biogas plant configurations are designed to meet this requirement. The study followed the cradle-to-grave principle used in LCA. Thus, inputs and outputs along the entire process chain, from biomass cultivation to biogas supply, are considered. Nevertheless, environmental impacts resulting from the provision of infrastructure such as buildings, machinery, and other infrastructure (e.g. roads or silage clamps), are disregarded, as findings of several studies have shown that their contribution to the total energy input over a time span of 20 years is negligible due to the large material and energy flows handled during this time (less than 4% according to Berglund (2006) and Bühle et al. (2011) and less than 10% according to findings by Hartmann (2006).

2.2. Impact categories

The assessment focused on the impact categories (1) primary energy, (2) greenhouse gas, (3) acidification and (4) eutrophication. These impact categories allow conclusions regarding the potential to save fossil resources and to mitigate climate change. They also help to evaluate the negative impacts of each biogas plant configuration on air quality (Cherubini and Strohmann, 2011). According to the Intergovernmental Panel on Climate Change (IPCC), the indicator for the impact category "greenhouse gas balance" is carbon dioxide equivalents ($CO_{2\text{-eq}}$) based on conversion factors of the three most important greenhouse gases: carbon dioxide, methane and nitrous oxide (Forster et al., 2007). The acidification balance is based on sulfur dioxide equivalents ($SO_{2\text{-eq}}$) from emissions of sulfur dioxide, nitrogen oxide, ammonia and hydrogen chloride. The eutrophication potential is based on the emissions of nitrogen oxide and ammonia, expressed as phosphate equivalents ($PO_{4\text{-eq}}$).

2.3. Biogas plant design

Biogas digesters are laid out based on the substrate mixture processed and its retention time (given for each biogas plant configuration in Section 2.4). The material of the digester's walls is reinforced concrete with an isolation of 160 mm. Biogas storages