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Method for assessing and improving the efficiency of agricultural biogas plants based on fuzzy logic and expert systems

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HIGHLIGHTS

- 4 performance figures for efficiency assessment and 8 for improvement analysis were selected.
- Method was developed by applying approaches of fuzzy logic and expert systems.
- Methodic approach enabled handling of uncertainty in data and modeling of expert knowledge.
- Method is proposed as tool for efficiency assessment/improvement of agricultural biogas plants.

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ABSTRACT

From previous research and monitoring of agricultural biogas plants it is known that there are various possibilities and needs for improving their efficiency. However, a reliable methodological approach for this purpose was missing. Therefore, the objective of this research was to develop a method for assessing and improving the efficiency of agricultural biogas plant operation. Firstly, four performance figures for efficiency assessment and eight performance figures for efficiency improvement analysis of the technical aspect of a biogas plant operation were selected. Based on these, the method was developed by applying approaches of fuzzy logic and expert systems. Using these approaches, it was possible to handle uncertainty in the assessment data and to model expert knowledge from the field of biogas technology. The method was tested with performance data from five agricultural biogas plants with combined heat and power production, located in Bavaria. The method was verified and validated, and is proposed as a comprehensive approach for assessing and improving the efficiency of agricultural biogas plants with respect to the technical aspect. To disseminate the method among potential users such as biogas plant operators or consultants, a web application is being developed. According to changes in the state of the art of biogas technology, continuous updating and improvement of the method is needed. For further development, the method should be adapted to other types of biogas plants, and extended to environmental and socio-economic aspects of biogas plant operation.

1. Introduction

Biogas is a form of renewable energy sources (RES) and can be obtained from any organic matter that is suitable for anaerobic digestion (AD). The methane content in biogas is 45–70% [1], which makes it a feasible energy carrier for different purposes [2]. Nowadays, in Asia and Africa, biogas is produced mainly in rural areas in small household facilities for cooking and lighting purposes. In the European Union (EU), in line with the Directive 2009/28/EC [3], political goals have been established in order to raise the share of energy supply from RES, in the form of electricity, heating and cooling energy, and biofuels for transport, including biogas. So far, the most common pathway of biogas utilization in the EU is the combined generation of heat and power (CHP). Other technologies for biogas utilization, such as upgrading and feed-in of bio-methane, are currently not relevant for a significant share of biogas plants. According to Biogas barometer for 2012 [4], Germany was the leading EU country regarding electricity generation from biogas, with 19426 GWh generated from more than 7000 operating biogas plants. Biogas production and utilization is significant in the United Kingdom and Italy as well. Most of the existing biogas plants are integrated in agriculture.

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The subject of this paper is the efficiency of agricultural biogas plants, which use animal manure, residues from agriculture and primary food processing, or energy crops as input materials, *i.e.* substrates. Considered are only facilities where the biogas is utilized for CHP generation, employing internal combustion engines coupled with electricity generators, since this technology is by far the most common one. Generally, biogas plants are complex biological-technical systems and there are many influences on their efficiency. Therefore, the efficiency of biogas plants should be defined using various performance figures [5] and has to be considered from different aspects. The efficient operation of agricultural biogas plants is the key for their economical feasibility and for environmental protection.

So far, several investigations have been conducted to monitor and assess the efficiency of biogas plants. In two successive projects funded by the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV), data on performance of 119 biogas plants were collected, and general measures for efficient operation of other existing facilities and for further development of biogas technology were derived [6,7]. In a project funded by the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT), 41 biogas plants in Austria were monitored, and a system of 13 performance figures was derived for assessing and comparing the efficiency of biogas plants [8]. The Bavarian State Research Center for Agriculture conducted extensive monitoring at 15 agricultural biogas plants in Bavaria over a time period of two to four years [9,10]. According to the obtained results, recommendations to operators for improvement of their biogas plants were given. The Association of German Engineers (VDI) proposed performance figures that could be used to define the efficiency of biogas plants with respect to technical, socio-economic and environmental aspects [11]. A detailed monitoring of two agricultural biogas plants in Austria was conducted by Bauer et al. [12], in order to determine more appropriate separation option of fermentation residues. Performance data collection and techno-economic analysis of energy generation from farm-scale biogas plant is presented in Akbulut [13].

Performance figures that describe the efficiency of household biogas installation in rural Africa and Asia were elaborated in several studies as well. However, in these cases effectiveness appears more important than efficiency, since the aim of constructing such biogas plants is energy provision at the site to reduce energy poverty. Failure of such installations may occur due to low quality construction or faulty operation and maintenance. In Cheng et al. [14], a fault tree approach was applied to assess technical aspects of small-sized biogas systems in Nepal. The selected criteria that describe technical issues of biogas plant operation in this study were grouped in several subsystems: structural components, biogas utilization equipment, piping system, biogas production and effluent disposal system. Yang and Chen [15] conducted an emergy analysis to assess the sustainability of Chinese biogas systems, and proposed a new emission indicator. The sustainability of biogas production in Kenya was assessed by a multi-criteria approach in Nzila et al. [16]. The selected criteria allow for the assessment of technical, environmental and economic aspects of the three dominant biogas plant designs: floating-drum, fixed-dome and tubular digester.

Methods for estimating the performance of biogas systems in terms of energy conversion have been reviewed and evaluated by Havukainen et al. [17]. The impact of using different substrates for biogas production on energetic and environmental factors has been analyzed by Bacenetti et al. [18]. An alternative method for analyzing energy flows in biogas plants and implications for plant design has been suggested by Scholwin and Nelles [19]. Cao and Pawlowski [20] provide an overview of energy efficiency assessment for anaerobic digestion in comparison with pyrolysis. Energy balances for biogas systems based on energy crops as substrates were elaborated by Salter and Banks [21].

In order to determine the environmental impacts from biogas systems based on different input materials, numerous investigations have been conducted, predominantly applying the methodology of Life Cycle Assessment (LCA) [22–28]. The LCA approach was also used to evaluate the most common technologies for digestate processing [29] and biogas upgrading [30]. Methodological differences of two LCA approaches for the assessment of environmental impacts from biogas plants were studied by Rehl et al. [31].

When considering multiple important aspects of biogas plant efficiency, multi-criteria methods for comprehensive performance assessment have to be used. Banks et al. [32] conducted a performance assessment for AD of source-segregated domestic food waste based on mass and energy balances. Data Envelopment Analysis (DEA) was applied by Braun et al. [33] as benchmarking tool to identify the most efficient plants and propose them as "best practice". The capabilities and limitations of a DEA approach for assessing the efficiency of agricultural biogas plants have been described in Djatkov and Effenberger [34]. As the main disadvantage of this approach, it was emphasized that the most efficient biogas plant could be identified only relatively, *i.e.* in dependence of the respective set of biogas plants to be assessed. In order to assess efficiency with respect to socio-economic and environmental aspects, DEA and Multi-criteria Decision Analysis (MCDA) were combined in Madlener et al. [35]. Expert knowledge from the field of biogas technology was incorporated to determine weights for performance figures. Additionally, this approach allowed for the qualitative assessment of biogas plants and their classification according to efficiency. In Djatkov et al. [36], fuzzy logic basics were applied to handle inevitable uncertainty in assessment data. Again, expert knowledge in the form of weights for performance figures was employed to improve the reliability of the method.

Procedures to improve the performance of biogas plants have been analyzed in various ways. Thorin et al. [37] evaluated the performance improvement of an industrial biogas plant. In order to investigate specific technological and operational faults, and identify possibilities for improvement, Lehner et al. [38] conducted research and monitoring on a number of agricultural biogas plants in Bavaria. Häring et al. [39] suggested measures for efficiency improvement based on the monitoring of 20 biogas plants including a detailed analysis of technical and operational conditions. Optimization approaches for biogas plants were also elaborated by Ward et al. [40] and Kana et al. [41].

From previous research on biogas plant efficiency, numerous performance figures have been derived that describe important technical and operational aspects of biogas plants. This has generated extensive expert knowledge about the efficient operation of biogas facilities. Also, as outlined above, various approaches for assessing the performance of biogas plants have been developed and applied in practice. However, there appears to be a lack of significant efforts to develop powerful assessment methods which can evaluate the efficiency of a particular biogas plant and indicate possible improvement measures, similar to what a professional consultant would do. In reality, such a complex task can be difficult and time consuming. Additionally, experts may apply approaches for efficiency assessment and improvement of biogas plants according to own knowledge and experience.

Therefore, the objective of this research was to develop a method for assessing and improving the efficiency of agricultural biogas plants in a systematic and reliable manner. The scope of the method is on biogas plants that operate under continental climatic conditions, use energy crops and animal manure as input materials, and utilize the biogas for combined heat-and-power generation with a capacity between approximately 100 kW_e up to about 1 MW_e. The developed method should contribute to more