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ScienceDirect

Energy Procedia 148 (2018) 846–851

Energy Procedia

www.elsevier.com/locate/procedia

73rd Conference of the Italian Thermal Machines Engineering Association (ATI 2018), 12–14 September 2018, Pisa, Italy

A short review of comparative energy, economic and environmental assessment of different biogas-based power generation technologies

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Abstract

Biogas can be utilized as a source of heat or power in single generation, cogeneration and multi-generation systems for production of useful commodities as power, heat or chemicals like hydrogen and methane. Different technologies can be employed for converting biogas as an energy carrier into final products. Besides, some strategies can be made for recovering the heat after the power generation processes for different purposes such as heating, cooling or even production of hydrogen or fresh water. Gas engines, gas turbines and solid oxide fuel cells (SOFCs) are the common technologies for power generation from biogas. This study investigates the novel biogas-based energy systems and assesses their energetic performance via efficiency evaluation as well as their environmental and economic performances.

Keywords: Anaerobic digestion; SOFCs; Biogas upgrading; combined heat and power (CHP); Methane

1. Introduction

In one hand, the global energy demand has been increased. On the other hand, the growing concerns about bio-

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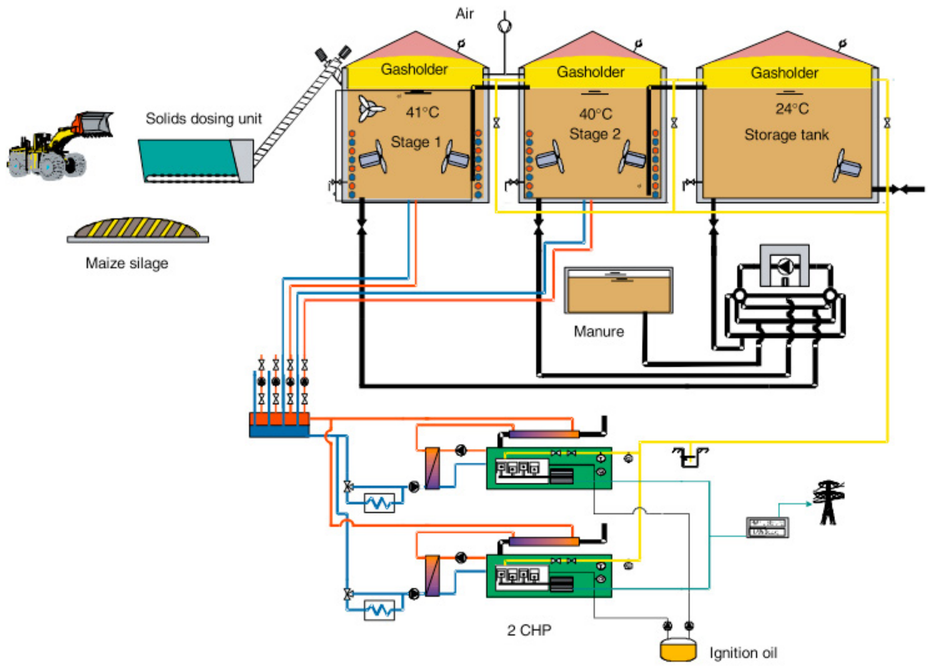
10.1016/j.egypro.2018.08.111

waste disposal and environmental problem have been raised [1,2]. These facts coupled with limited fossil resources means that alternative energy resources are necessary [3,4]. Nowadays, energy carriers (e.g. hydrogen and methane) produced by thermochemical and biological conversion systems have been attracted increasing attention as a promising alternative to the fossil fuel [5,6]. Different technologies can be employed for converting biogas as an energy carrier into final products. More and more interests have been focused on biogas upgrading, biogas combined heat and power (CHP), biogas solid oxide fuel cells (SOFCs) [7,8]. Based on local energy renewable policies and regulations, the biogas plants of each country are different. For example, Sweden uses biogas plants in which the biogas is directly used as a vehicle fuel after a filtration process [9]. While, in Germany, the biogas plant usually is integrated with gas engine or gas turbine to provide heat and electricity [10]. Schematic 1 depicts a typical biomethane-CHP plant which is a two-stage digestion plant in which hydrolysis and methanation reactions take place in separate reactors. However, in addition to the traditional biogas CHP technology, a new wave of interest in developing a new energy system based on biogas plant and SOFC has been created which is due to its higher energy efficiency [11]. In this review article we explore that which biogas plant pathway is feasible and to reach this goal, different biogas plants are sassed from the viewpoint of energy, environment, and economy. In fact, the short-review provides useful data by which the decision makers can choose the proper biogas utilization modes.



Schematic 1. Two-stage biomethane-CHP plants

2. Biomethane-CHP plants

As already mentioned earlier, biogas is mostly applied for providing electricity and is generally obtained by the small to medium-scale installation on farms in the agricultural sectors as well as in larger AD plants for waste digestion. Table 1 shows the results obtained from a survey of biogas plant operators in 2015, regarding the kind and number of biogas production. As seen, in 2016, more than 95% of biogas plants are assigned to the Biomethane-CHP plants.

Table 1. The kind and number of biogas production plants in Germany in 2016 [10].

Type of biogas production plants	**Number**
Agricultural biogas plants	appr. 8200
thereof manure-based small-scale plants (£ 75kW) according to § 27b EEG 2012/ § 46 EEG 2014	560
Biowaste digestion plants (share of organic waste larger than 90 %)	appr. 135
AD plants based on organic waste and manure/ energy crops (share of waste smaller than 90 %)	200
Biogas upgrading plants (biomethane)	196
Biogas production plants, total	appr. 8700

It is important to note that, in Germany, 17.2% of renewable energy based electricity generates from the biogas which is about 32.37TWh_{el}. Figure. 1 shows the electricity production in Germane from Biogas in 2015 in kWhel [10].

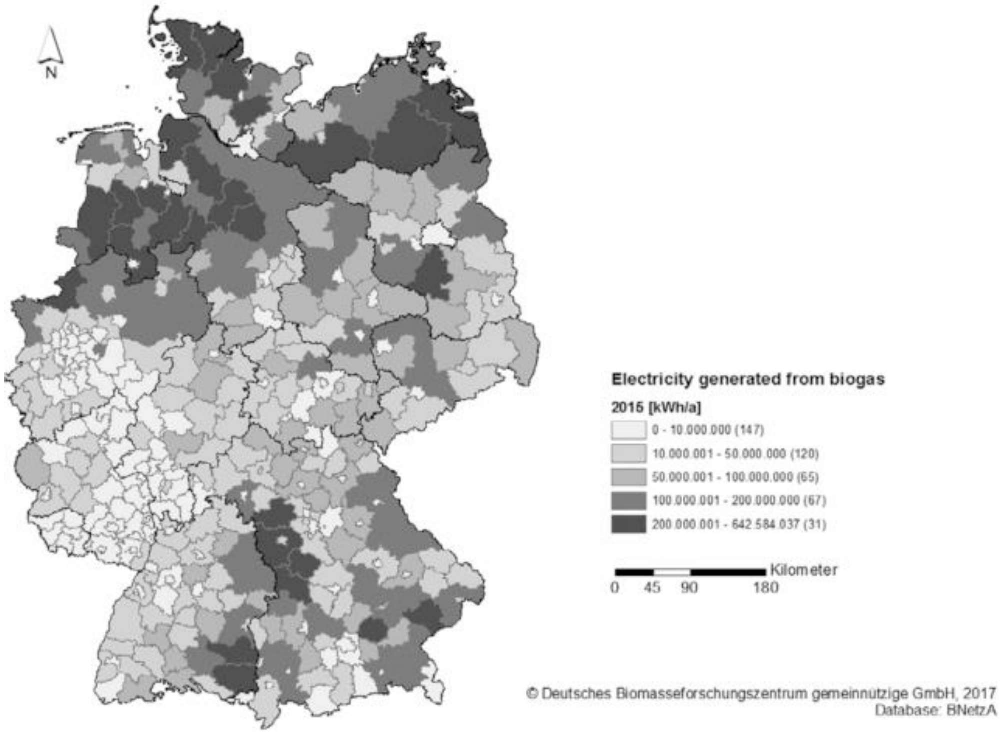


Fig.1. Electricity production distribution from Biomethane-CHP plants in Germany, according to DBFZ allocations of database of BNetzA [10]

Although lots of Biomethane-CHP plants have been constructed in developed countries, the recent studies show the technology still faces major problems. For example, Bin Wu et al. assessed a biogas system with three utilization pathways from the Energetic-environmental-economic point of view. The assessment results indicated that Biomethane-CHP plants have the lowest systematic energy efficiency than a biogas plant integrated with SOFCs or biogas upgrading pathway. Energy efficiencies of a biogas system with three utilization pathways are shown in Table 2 [9].

Table 2. Energy efficiency of three biogas utilization systems

Systems	Net electricity output (MJe/day)	Net heat recovery (MJth/day)	Net electric efficiency (%)	Net heat efficiency (%)	Energy efficiency (%)
Biogas upgrading	-	-	-	-	46.5
biomethane-CHP plants	4139.8	5202.5	13.8	16.6	30.4
Biogas@SOFCs	5286.5	3530.6	20.4	12.5	32.9

3. Biogas upgrading

As mentioned in Table 1, among the three aforementioned utilization pathways, biogas upgrading has higher energy efficiency than its counterparts. Although the results reported by Bin Wu et al. show that the utilization of biogas as fuel supplied to the natural gas grid, or for vehicle fuels are preferred than other pathways, there are still some concerns hinder its wide use. Actually, it should be noted that the energy efficiency of the biogas upgrading system was calculated by the so-called output-input ratio method. This method relies solely on the lower heating value (LHV) of feedstock and methane, which is different from the method used in assessing other technologies. For the calculation of the energy efficiency of the biomethane-CHP plants and Biogas@SOFCs, LHV based net electric efficiency and heat are important factors [9]. In other words, the proposed method for calculating biogas upgrading energy efficiency does not go beyond the biomethane production, not considering emissions, energy losses and costs related to the end use (e.g. transport fuel or domestic heating purposes). Moreover, the introduction of such a fuel in a pipeline requires removal of contaminants other than excessive CO2, which is energy and cost demanding [12]. These are the reason why most biogas plants directly use biomethane in an internal reciprocating combustion engine (ICE), gas turbine, organic Rankine Cycle, fuel cells.
Anyway, there are some biogas plants works based on biogas upgrading. In this technology, purification system is of prime importance. Various types of technologies have been summarized in Table 3 [13].

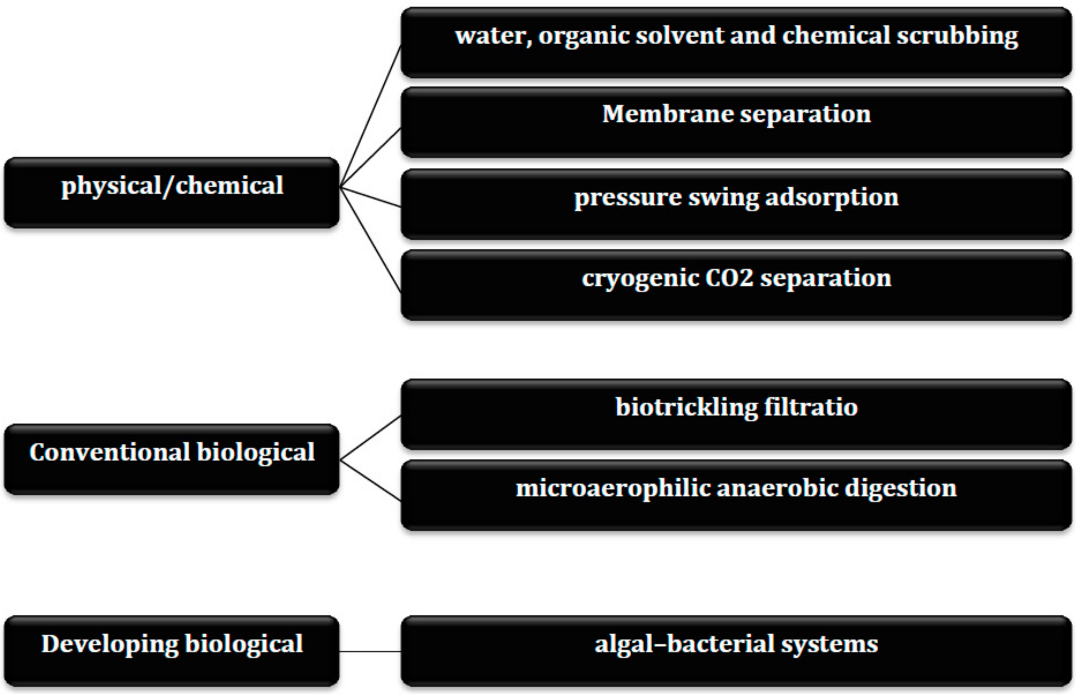


Fig. 2. Biogas upgrading technologies.

Recently, Toledo Cervantes and co-workers investigated an innovative algal-bacterial photobioreactor and a conventional activated carbon filter coupled with a water scrubber as an alternative technology to the physical-chemical technologies. The results show that the investment cost for the algal-bacterial photobioreactor was 1.6 times higher than that of its physical/chemical counterpart due to the biomass drying unit required to produce an algae-based fertilizer. However, the operating cost of the physical/chemical technology was ~7 times higher due to the frequent replacement of the activated carbon. In the following section, we will discuss Biogas@SOFCs technologies and their advantages and disadvantages [13].

4. Biogas@SOFCs

Although internal combustion engine has been considered as the most widespread electricity generator system at international level, it still holds back to some issues at both global and local levels, such as the formation of thermal NOx due to the Zeldovich mechanism and the generation of primary and secondary particulate matter [12,14]. To address this issue, Biogas@SOFCs has recently attracted the researcher's attention due to the higher electric energy per unit of input energy and better tolerance to contaminants, compared to traditional systems such as reciprocating engines or gas turbines. Moreover, since the energy consumptions of the biogas utilization system with Biogas@SOFCs are satisfied via self-use of the energy generated inside the system. Thus, the biogas utilization system with SOFCs is more environmentally friendly than the biogas upgrading pathway [15] Rillo et al, evaluated the environmental performance of an SOFC fueled with sewage biogas and compared it with traditional technologies (internal combustion engines and microturbines) using the same fuel. The results show that SOFC can be of a potential method for future electricity generation application in biogas plants. [11]

5. Conclusion

According to recent publications, we can reach the conclusion that the development of fuel cells is promising to enable the distributed generation of electricity in the near future. Thus, researchers try to design a novel energy system based on AD biogas plant and SOFCs. The environmental, economic analyses had revealed that the use of biogas from biowaste in a solid oxide fuel cell is more feasible than both biomethane-CHP plants and biogas upgrading. As for the energetic feasibility, the order is biogas upgrading> Biogas@SOFCs > biomethane-CHP plants. However, as already mentioned, the different aspects of the end user energy needs must be considered regarding the biogas upgrading. So, it is recommended that researchers in the field of anaerobic digestion process pay close attention make the Biogas@SOFCs system more efficient and comparable to the current conventional biomethane-CHP plants.

Acknowledgments

The authors would like to thank Eng. Federico Sisani from the department of engineering, University of Perugia, for his kind support for the better production of the paper.

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