Applied Energy 229 (2018) 922–935

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Assessment of a combined cooling, heating and power system by synthetic use of biogas and solar energy

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HIGHLIGHTS

- A new CCHP system based on biogas steam reforming is proposed for application.
- Key process experiment of the reforming process validates the system feasibility.
- Integrated performances are improved by synthetic use of biogas and solar energy.
- Payback period of the new system reduces by 49.5% comparing to conventional ones.

ARTICLE INFO

Keywords:
Biogas steam reforming
Solar energy utilization
Trigeneration
Key process experiment
Hourly dynamic simulation
Economic analysis

ABSTRACT

Anaerobic digesters should always be kept warm for a stable biogas yield. The conventional method for digester temperature maintenance results in a considerable waste of energy and pollution of the environment by directly firing biogas. Biogas-driven trigeneration systems can improve biogas utilization efficiency; however, the waste heat from the power engines is limited by the digester's thermal insulation, and additional fossil fuels are consumed to supplement the thermal power. To ease fossil fuel energy consumption and enhance the efficiency of biogas utilization, this paper presents a combined cooling heating and power (CCHP) system with synthetic use of biogas and solar energy. Solar energy is first transformed into syngas chemical energy through a chemical reaction called biogas steam reforming, and then the chemical energy is used for trigeneration in a conventional CCHP subsystem. Experimental research was conducted on the key process of biogas steam reforming to validate its feasibility. Hourly dynamic simulations of the proposed system were conducted by the mathematical models established using Lhasa, Tibet weather data. A biogas-fired CCHP system and a solar Dish/Stirling power system were adopted as reference systems, and a comparative analysis showed that the synthetic use of biogas and solar energy in the proposed system improves the annual electricity production by 8.70%, improves the refrigeration by 2.57%, and reduces the natural gas consumption by 8.66%. In addition, the direct CO_2 footprint in the proposed system is 8.20% lower than that in the reference systems. Finally, an economic study was conducted to validate the technical feasibility of the new system. The study offers a new method of using biogas and solar energy for an improved integrated performance.

1. Introduction

The growth of the global population and worldwide industrial development contributed to increasing the construction of medium- and large-scale sewage and waste treatment plants. Taking sewage treatment plants (SWTP) as an example, to minimize environmental pollution and recycle water resources, SWTPs play a pivotal role in collecting and treating the sewage before being ducted to the water cycle or drained into rivers or the sea; meanwhile, between 40% and 60% of the dissolved organic matter in the sewage are transformed by anaerobic fermentation into a non-fossil combustible gas (called biogas) with a high methane content of approximately 50–70% [1]. As a renewable energy source, biogas is regarded as a prominent choice to meet increasing energy demands and ease the greenhouse effect [2]. However, the enormous energy benefits of using biogas in sewage treatment plants or some other biogas plants is still not widely exploited, and

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https://doi.org/10.1016/j.apenergy.2018.08.037
Received 28 May 2018; Received in revised form 1 August 2018; Accepted 6 August 2018
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Nomenclature

A	total surface area of the digester [m^2]
A_a	collector aperture area [m^2]
B_0	ultimate methane yield, L (CH_4)/g (VS)
COP	coefficient of performance
COP_{el}	COP of the electric chiller
HRT	hydraulic retention time [day]
K	kinetic parameter
LHV	low heating value of fuel [kJ/kg]
M	CO_2 emission from the combustion [CO_2/Nm^3]
P	pressure [bar]
Q	thermal energy [kW]
Q_s	gross solar energy input [kW]
S_0	influent total volatile solid concentration, g (VS)/L
T_a	ambient temperature [°C]
T_{col}	collecting temperature [°C]
T_r	digester temperature [°C]
T_{ref}	reforming temperature [°C]
T_w	average operating wall temperature in the cavity [K]
U	overall heat transfer coefficient W/(m^2 K)
VS	volatile solid
W	power output [kW]
X_{sol}	solar thermal share [%]
W	power output [kW]
X_{sol}	solar thermal share [%]
η_b	gas boiler efficiency
η_c	optical efficiency
η_o	solar collector efficiency
$\eta_{r,fg}$	recovery efficiency of exhaust gas
$\eta_{r,jw}$	recovered efficiency of jacket water
γ_v	CH_4 production rate [m^3 (CH_4) m^{-3} day^{-1}]

Subscripts

bio	biogas
c	cooling
el	electricity
f	fuel
fg	flue gas
h	heating
jw	jacket water
net	net output
ref	reference system
ng	natural gas
rad	solar radiation
sol	solar heat
0	environment state

produced biogas is used in a primitive and simple way by direct firing in most industrial and civilian applications [3].

To pursue the maximum benefits of using biogas, combined heat and power (CHP) systems are adopted, which provide an effective approach for producing electric power by biogas combustion in a power generation unit and exporting hot water to maintain the stable condition of the fermentation tank. Currently the design and optimization of CHPs are primarily based on mathematical tools to integrate different types of energy conversion technologies, with one or more targets of energy efficiency, annual energy consumption, annual cost, or CO_2 emissions, or the weighted combination of two or more of these [4,5]. Some studies explored the thermal performance of the CHP or CCHP fired by blended fuel formed by biogas and natural gas [6,7]. Basrawi et al. [8] optimized the techno-economic performance of a biogas-fired CHP via selecting a proper capacity of the power generation unit. The power output capacity of 30, 65 and 200 kW were researched for using biogas from sewage treatment plants, and it was found that the optimal fuel input of the gas turbine approximately equals the biogas production of the digester. The smaller size of the power generation unit is preferred when heat demand greatly fluctuates. However, one significant problem of CHP systems exists in hot climate regions: substantial thermal energy is discharged into the environment because the required thermal energy for the digesters is not very great, especially in summer, leading to serious environmental pollution and a considerable waste of energy. Chen et al. [9] conducted a study on the annual performance analysis of different CCHPs based on sewage treatment plants in hot climate regions. The redundant thermal energy in summer is used to produce cooling energy by an absorption refrigerator to meet the demands of the district cooling in nearby buildings. Bruno et al. [3] conducted an environmental and economic study of biogas-fired CCHPs with different system configurations in a colder region. They found that the best options are those that utilize all biogas and excess natural gas in the gas turbines to completely reach the heating demands of the sewage treatment plant. Although biogas-fired CCHP improved the efficiency of energy utilization, substantial fossil fuels from natural gas pipeline networks and electric power from power grids are still needed, especially in the colder areas.

Solar energy, a clean renewable energy source, has great potential to further reduce the dependence on external fossil energy sources, and improve thermal performances [10,11]. The two main components in biogas are methane and carbon dioxide. Thermochemical performance of the solar driven methane dry reforming process in foam reactor was studied by Chen at al. [12,13], especially, the effects of the foam structural parameters on the reaction performance were researched. Rathod et al. [14] experimentally studied the biogas reforming process driven by a dish solar collector, and the experimental results were compared with the theoretical results.

At the system level, there are multiple integration forms of solar energy in CCHP systems, such as photovoltaic power generation [15,16], heating cycle fluids [17,18], solar water-heating systems and driving absorption chillers [19,20]. However, only a few studies can be found in the open literature that integrate solar energy into a biogas-fired energy system. Gazda [21] proposed a distributed energy system driven by solar energy and biogas. A photovoltaic (PV) system was adopted to transform solar energy into electric power. In addition, a conventional CCHP, consisting of a power generation unit, an absorption chiller and a heat exchanger, was adopted for trigeneration by using biogas. This integrated system simply combined different renewable energy utilization methods, and did not consider the connection between renewable energy sources. Zhang et al. [22] proposed a hybrid concentrating solar power (CSP) and biogas power plant, in which biogas is used as supplementary fuel when solar energy is insufficient. The low-temperature waste steam from the steam turbine was adopted to provide thermal energy for the digester insulation. Mehr et al. [23] proposed a solar-assisted integrated biogas solid oxide fuel cell system. When the heat from the biogas solid oxide fuel cell cannot satisfy the digester heat demand, a concentrating solar thermal (CST) system is used for heat supplement. The current biogas-fired energy systems just feature the simple and direct use of solar energy by photovoltaic cells, concentrating solar thermal or concentrating solar power systems without considering the strong complementarity between these renewable energy sources. Usually, biogas is burned in an engine through combustion and then converted into power, heat and cooling energy in a conventional CCHP system. However, the irreversibility is still large during the biogas combustion process, and the use of biogas chemical energy before combustion is not considered in the current studies. In addition, by synthetic use of biogas and solar energy, system initial investment costs are expected to decrease.

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