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Proposal and assessment of a novel integrated CCHP system with biogas steam reforming using solar energy

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HIGHLIGHTS

- A novel CCHP system with biogas steam reforming using solar energy is raised.
- Chemical and physical energy of biogas is efficiently used in a cascaded way.
- The energy quality of concentrating solar heat is promoted in the system.
- A parametric analysis is adopted to optimize the thermodynamic performance.
- A typical-day study is conducted to explore the general operation features.

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ABSTRACT

The conventional way to utilize biogas either is energy-intensive due to biogas upgrading or causes huge waste of energy grade and environmental pollution by direct burning. This paper proposes a biogas and solar energy-assisted combined cooling, heating and power (BSCCHP) system that upgrades the caloric value of biogas before combustion by introducing a thermochemical conversion process that is driven by solar heat. Adopting commercially established technologies including steam reforming and parabolic dish concentrators, the system exhibits an enhanced system exergy efficiency, and the technology considerably reduces the direct CO_2 footprint and saves depletable fossil fuel. With a solar thermal share of 22.2%, the proposed system not only has a high net solar-to-product thermal and exergy efficiency of 46.80% and 26.49%, respectively, but also results in a commensurate 18.27% reduction of the direct CO_2 footprint compared with the reference individual systems. The effect of critical parameters in the biogas steam reforming process on the system performance was studied. A proper selection of the steam/carbon ratio leads to the optimal direct CO_2 footprint and system exergy efficiency. Pursuing a very high conversion of biogas by improving the reforming temperature is not a wise choice from a system perspective. Finally, a typical-day dynamic simulation was conducted to preliminarily explore the general operation features. This study may provide a new way to efficiently use the renewable energy in the distributed energy system.

1. Introduction

Distributed combined cooling, heating and power (CCHP) systems or combined heat and power (CHP) plants are broadly considered an energy-saving and environmentally friendly way to use both fossil and renewable fuels and to make a significant contribution to the development of sustainable energy [1]. Clean and efficiently obtained renewable energy resources are sustainable alternatives to the depletable fossil fuels in conventional CHP/CCHP systems [2].

As a renewable energy, biogas, which is produced from organic wastes by applying anaerobic biological fermentation methods, is being seriously and widely promoted as a significant choice to satisfy the growing energy demand of rural areas in developing countries and decarbonize the current energy conversion systems. The Chinese rural biogas development model primarily takes the form of small-size household biogas pools [3]. In these rural areas, the biogas produced from the anaerobic fermentation digester is either used in boilers or directly burned in flares for supplying hot water or for cooking [4], which causes a huge waste of energy grade and environmental pollution. At present, purified and upgraded biogas (with a high concentration of methane) is a type of biomethane that can be compressed and liquefied as an automotive fuel or injected into a public natural gas

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Nomenclature

A_a	aperture area of dish concentrator [m^2]
A_c	entrance aperture area of receiver [m^2]
A_w	cavity internal area of receiver [m^2]
C	geometric concentration ratio
COP	coefficient of performance
Gr_L	Grashof number based on length L
g	gravitational acceleration, 9.807 m/s^2
h_c	convective heat transfer coefficient [$W/(m^2 K)$]
k	thermal conductivity of the ambient air [W/m K]
LHV	lower heating value of fuel [kJ/kg]
M	the amount of CO_2 emitted from the combustion of CH_4 and CO_2 density [1.96 kg CO_2/N m^3]
m	mass flow rate [kg/s]
Nu_L	Nusselt number based on length L
P	pressure [bar]
Q	heat [kW]
T_a	ambient temperature [°C]
T_r	reforming temperature [°C]
T_w	average operating wall temperature in the cavity [K]
TIT	turbine inlet temperature [°C]
W	power output [kW]
X_{sol}	solar heat input share [%]
η_b	gas boiler efficiency [%]
η_c	collector efficiency [%]
η_{ex}	exergy efficiency [%]
η_o	optical efficiency [%]
ε_c	radiative emissivity of cavity
ε_{eff}	effective infrared emittance of cavity
σ	Stefan–Boltzmann constant, $5.67 * 10^{-8}$ $W/(m^2 K^4)$

Subscripts

c	cooling
e	electrical
f	fuel
h	heating
net	net output
ref	reference system
rad	solar radiation
s	steam
sep	separate generation system
sol	solar heat
0	environment state
1, 2…18	states on the cycle flow sheet

pipeline network. However, biomethane is commercially acquired mainly by CO_2 separation and pressurization to approximately 20 MPa with compressors. The energy consumption of such techniques is extremely high, between 0.3 and 0.5 kW h/N m^3 raw biogas, which consumes up to approximately 10% of the energy content of the raw biogas [5]. The present biomethanation technology is too energy intensive, and the proposal of novel energy systems is sought to utilize the biogas more efficiently.

Distributed energy systems (DESs) that are located close to the user side and identified as a crucial complement to conventional centralized power networks are capable of using biogas efficiently with some of the commercially available small-scale technologies. Adopting mathematical methods to integrate different types of energy resources and energy conversion systems for a higher overall thermodynamic, economic and environmental performance of a DES has recently become prominent [6,7]. However, the proposal and design of a novel DES based on biogas have been reported in only a few reports in the literature. Gao et al. [8] proposed a novel biogas-and-heavy-oil hybrid-driven distributed CCHP system based on the principle of energy cascade utilization. Diesel engines are adopted to supply electric power. The waste heat from the jacket water is used to drive a liquid desiccant dehumidification system to treat the latent heat of air. The exhausted heat of discharge smoke first drives an absorption refrigeration system for treating the sensible heat of air and then produces hot water by exchanging the heat in a heat exchanger. The energy saving ratio of fossil fuel is 34%, which is 14 percentage points higher than the energy saving ratio of the conventional CCHP system. Bruno et al. [9] considered the effect of the moisture of biogas and the temperature of input air on the system thermodynamic performance and proposed a novel biogas-driven distributed energy system for electric power, cooling and heating (BCCHP). However, the products are mainly consumed in the internal energy system rather than by the nearby users. The chilled water produced in an absorption refrigerator is used to cool the biogas and the input air. The hot water produced in an exhaust recuperator is used to keep the digester sufficiently warm to achieve a higher biogas production rate. This type of system design suits an organic waste treatment plant such as a sewage treatment plant. To improve the energy utilization performance and reduce the carbon dioxide footprint in the biogas utilization process, Budzianowski et al. [5] combined the pressurized anaerobic digestion (PAD) technology with the conventional CHP system. PAD technology causes methane enrichment in biogas by limiting the amount of CO_2 that is liberated to biogas under hyperbaric conditions and slightly improves the power generation efficiency of the CHPs by approximately 1–2% due to the higher caloric value in biogas and flame velocity in the combustion process [10]. However, PAD technology needs to pressurize the anaerobic fermentation digester to as high as 5 MPa by the natural accumulation of biogas, which brings the problems of preventing gas leakage and feeding the feedstock. Gazda [11] proposed a type of DES based on the multi-renewable energy sources. Biogas is utilized in the CCHP technology that consists of an internal combustion engine, adsorption machines and heat exchangers, and solar energy directly transformed into electric power by a photovoltaic (PV) system. This type of system (BCCHP + PV) uses just biogas and solar energy simply and separately without crossover. These biogas-fired CHP/CCHP systems mentioned in the literature have, to some extent, realized the cascade utilization of the physical energy of the input energy and reached a higher overall energy efficiency compared with the separate production of utilities. However, they still feature the direct use of solar energy or power generation waste heat and have not addressed the chemical energy utilization of the biogas in the system integration. Chemical energy utilization of the biogas has the potential to improve the system performance further by utilizing the biogas and solar energy synthetically and organically. Currently, biogas steam reforming has been widely researched for either obtaining synthesis gas (a mixture of H_2 and CO) as an appropriate raw gas for the production of fuels such as gasoil, alcohols, kerosene, aldehydes, gasoline or acquiring hydrogen for fuel cell applications [12,13]. Bhale and Rathod et al. [14] conducted a novel and detailed experiment in biogas reformation driven by a micro-dish collector with a 16-m^2 concentrating mirror and verified the feasibility of this technical route. The experimental finds contributes significantly to the application of this technology into the energy systems. However, none of the literature has reported a study of the integration of DES based on biogas with such a thermochemical conversion process.

In this paper, we propose a novel BSCCHP system integrated with the renewable energy sources (biogas and solar energy) that upgrades the caloric value of biogas before its combustion by introducing a thermochemical conversion process. Unlike a conventional CCHP system in which solar energy is directly transformed into the electric power or is used directly for heat generation, the solar dish collector in