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Using solar energy to improve the energy performance of tri-generation systems for sewage treatment plants

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Abstract

A feasibility study was conducted on using solar energy in a conventional tri-generation system for sewage treatment plant application. Generally conventional CHP/CCHP systems can improve the biogas utilization efficiency, however, the waste heat from the power engines is limited for the digester thermal insulation most time in some colder areas, and the additional natural gas is consumed for supplement. This paper proposes a biogas and solar energy-assisted tri-generation system that upgrades the caloric value of biogas before combustion by introducing a thermochemical conversion process. The hourly dynamic energy performances of the proposed and reference systems were simulated by the established mathematic models under Tibet Lhasa weather data. Using solar energy not only reduces the dependence on the external fossil fuel, but also increase the output electric power and cooling energy. The saved natural gas in the whole year can reach 142,757 Nm^3. This study may provide a new way to efficiently use the solar energy to improve the energy performance of tri-generation systems.

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Keywords: concentrating photovoltaic; concentrating solar power; Kalina cycle; solar energy utilization.

1. Introduction

To minimize environmental pollution and recycle the water resources, sewage treatment plants (SWTP) have a pivotal role in collecting and treating the sewage before being ducted to the water cycle or drained into the river or sea, meanwhile, between 40% and 60% of the dissolved organic matters in the sewage are also transformed into a

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non-fossil combustible gas (called biogas) with a high methane content of around 50–70%. As a renewable energy, biogas is being seriously and widely promoted as a significant choice to satisfy the growing energy demand and decarbonize the current energy conversion systems [1]. However, this enormous energy benefits of using biogas in SWTPs is still not widely exploited, and the biogas produced is either used in boilers or directly burned in flares in most plants [2].

To pursue the maximum benefit of using biogas, combined heat and power (CHP) systems are adopted in some large sewage treatment plants, providing effective approach for generating electricity by burning the biogas and producing hot water as by-product for maintaining the required temperature of the sludge digester [3]. Currently the design and optimization of CHPs is mainly 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 emission, or the weighted combination of two or the weighted combination of two or more of these [4, 5]. However, one significant problem of CHP systems exists in hot climate regions: substantial heat has to be released to the environment through the radiators due to the low heating demand of digesters in summer, leading to significant energy waste. Chen et al. [3] conducted a study on energy and economic benefits of converting a CHP to a combined cooling, heat and power system (CCHP) for sewage treatment plants in subtropical area. The redundant thermal energy in summer is used to produce cooling energy by an absorption refrigerator for either lowering the inlet air temperature of the CCHP or realizing the district cooling for nearby office buildings or residential buildings. When CCHPs are implemented in SWTPs located in cold regions, the waste thermal energy from the CCHP is insufficient for maintaining the required temperature of the sludge digester [4]. Bruno et al. [2] conducted an environmental and economic study of CCHPs with different system configurations in a colder region. They found that the best options are those that utilize all the available biogas and additional natural gas to completely reach the heating demands of the sewage treatment plant. Though the CCHP improve the efficiency of energy utilization and reduces dependency on fossil fuels to some extent, substantial fossil fuels from natural gas pipeline network and electric power from power grid are still needed seriously.

Solar energy, a kind of clean and renewable energy, has great potentials to further reduce SWTPs' dependence on the external energy sources. However, only a few studies can be found in the open literature to integrate the solar energy into a biogas-fired CCHP. Even so, they just feature the simple and direct use of solar energy by photovoltaic cells (PV) or solar-assisted heating system [6, 7]. Moreover, none of the studies focus on the possible additional benefit of using solar energy in sewage treatment plants. In this paper, solar energy and biogas are both considered to be used in a new CCHP system in SWTP. Unlike a conventional CCHP system in which solar energy is directly used as mentioned before, solar energy in the proposed system is used in a new way by introducing a thermochemical conversion process and stored in the form of syngas. The mathematical model of the proposed system was established in detail and a whole year performance was given.

2. System description

Fig. 1 shows the flow diagram of biogas-and-solar-driven CCHP, which consists of a solar utilization subsystem and a CCHP subsystem. In the solar utilization subsystem, the reformer is the key component, in which the biogas reforming process occurs, as follows [8]:

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \quad \Delta H= 247.3 \text{ kJ/mol} \tag{1}$$

This reaction is known as methane dry reforming, which is able to transform two types of greenhouse gases (CH_4 and CO_2) into synthetic fuel, and is a highly endothermic reaction process. The required thermal energy is supplied by a parabolic dish collector that is easy for accomplishing the miniaturization in structure and extremely suitable for integration into distributed energy systems. Unlike the parabolic trough or solar tower with relatively high cosine loss, the dual-axis tracking of the parabolic dish collectors eliminates the loss of this part and increases the collecting efficiency. The runtime of the biogas reforming relies on the period of available sunlight. When solar energy is sufficient, more biogas from the biogas holder participates in the reforming process. If the produced syngas exceeds the requirement of the CCHP subsystem, the surplus syngas is stored in a syngas holder. When solar energy is unavailable or night comes, the stored syngas in the syngas holder is ducted into the internal combustion engine (IEC), making the IEC always runs under the rated condition. The production capacity of biogas is almost constant due to