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Using anaerobic digestion of organic wastes to biochemically store solar thermal energy

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ABSTRACT

Solar energy is the most abundant energy resource with the potential to become a major component of a sustainable global energy solution. However, unsteady energy flow and low energy density make it difficult to collect, convert, and store solar energy, which is why current solar power generation technologies have limited applications. This paper comprehensively studied the integration of solar thermal collection with different anaerobic digestion operations to form solar-bioreactor systems in order to realize biological storage of solar energy and solve the issues that solar energy generation encounters. The experimental comparison of manure digestion and co-digestion concluded that co-digestion had a better methane yields with a minimum difference between mesophilic and thermophilic conditions. The energy analysis of solar-bioreactor systems with both manure digestion and co-digestion at different bioreactor sizes further concluded that solar-bioreactor systems with mesophilic co-digestion was the preferred system to store solar energy into methane biogas. The optimal solar-storage efficiencies for the three systems of 10, 100, 1000 m^3 were 67%, 68% and 70%, respectively. The corresponding solar-bioreactor system efficiencies were 82%, 88%, and 89%.

1. Introduction

The earth surface receives around 4176 PWh of solar energy, about 29 times the current global consumption of primary energy (144 PWh) [1,2]. Thus, solar radiation has the potential to become a major component of a sustainable global energy solution. Currently, solar energy only presents a trivial portion of global energy consumption. Around 0.1% of the total primary energy supply of United States is from solar radiation [3]. Unsteady energy flow and low energy density make it difficult to collect, convert, and store solar energy, which is why solar power generation technologies have limited applications [4]. Addressing these issues creates a good opportunity for scientific and industrial communities to make significant technological contributions to solar energy utilization. Functional solar power generation requires two basic components: solar collection and energy storage. Solar radiation falls on a collector that converts a fraction to electricity or heat. The energy storage then holds the excess energy produced during sunny days and releases it at night and cloudy days to create a steady supply of energy.

Current technologies of solar thermal energy storage systems can be classified into the following categories: sensible heat storage, latent heat storage, and thermochemical heat storage [5]. Sensible heat storage utilizes the heat capacity and the change in temperature of a storage medium, such as water, during a charge and discharge heat exchange process. The sensible heat storage is a simple and economic method to store solar energy. However, low storage temperature, large volume of medium, and huge heat loss limit its applications [6]. Latent heat storage methods store energy through phase change. Salt hydrates, metallics, fatty acids, and paraffin and paraffin waxes are considered promising candidates of solar thermal storage [7,8]. The main problem with these phase change heat storage materials is that none of them satisfies the

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Notation and nomenclature

A	surface area of the reactor, m^2
A_c	area of solar collectors required for energy needed by reactor, m^2
A_{cV}	area of solar collectors required for energy needed by reactor, $m^2 \cdot m^{-3}$
Cp_{manure}	specific heat of the manure, J kg^{-1} °C^{-1}
$E_{heating}$	the heating energy consumed by incoming feed, MJ
$E_{heatingVol}$	energy consumed per hour per cubic meter of incoming feed to heat the incoming manure and waste, MJ m^{-3}
E_{solar}	hourly energy collected by solar system, MJ m^{-2}
E_{total}	total energy consumption, hourly based, MJ
$E_{consumed}$	energy consumed per hour to maintain reactor temperature at T_R, MJ
$E_{consumedVol}$	energy consumed per hour per cubic meter of slurry to maintain reactor temperature at T_R, MJ m^{-3}
HRT	hydraulic retention time, days
I_n	energy generation from the solar thermal collector, W m^{-2}
I_{solar}	solar radiation received on a surface normal to the sun during the 60-min period ending at the timestamp, W m^{-2}
MC	moisture content of the manure, %
M_{in}	mass of incoming manure and waste into the reactor, kg
P	difference between the temperature of the outlet fluid of the solar panels, and the ambient temperature
Q_{out}	heat lost by the reactor, W
R_{12}	thermal conductivity of insulation, °C m^2 W^{-1}
T_A	ambient temperature, °C
T_i	outlet temperature of the solar panels, °C
T_{manure}	initial temperature of the incoming manure, °C
T_R	internal temperature of the reactor, °C
V	volume of the reactor, m^3
ρ_{manure}	density of the manure, $kg \cdot m^{-3}$
η_{solar}	efficiency of the solar vacuum tube collector
Total methane energy	the total amount of energy from the methane generated from anaerobic digestion, MJ. It is calculated by: Total methane energy = volume of methane produced (m^3) × 38 (MJ/m^3), where 38 MJ/m^3 is the heating value of methane.
Net energy output	the net energy output of total methane energy, energy required to heat and maintain the reactor, and solar energy stored in the methane, MJ per cubic meter of effective reactor volume. It is calculated by: Net energy output = total methane energy + solar energy stored in the methane − energy required to heat and maintain the reactor.
Solar energy stored in methane	the portion of solar energy that is used by the reactor to heat and maintain the reactor temperature, MJ per cubic meter of effective reactor volume.
Solar storage efficiency	it is used to describe the percentage of stored solar energy over the total solar energy collected from solar thermal collector. It is calculated by: Solar storage efficiency = solar energy stored in the methane/total solar energy collected by the solar thermal collector *100%.
Solar-bio-reactor system efficiency	it is used to describe the overall system efficiency. It is calculated by: Solar-bio-reactor system efficiency = Net energy output/total methane energy *100%.

desirable thermo-physical, kinetics and chemical properties of an ideal thermal storage medium [8]. In thermochemical energy storage, energy is stored after a dissociation reaction and then recovered in a chemically reverse reaction, which shows a much higher storage density than the other types of thermal storages. Extensively researched thermochemical storage materials include metal oxides, $FeCO_3$, $Ca(OH)_2$, and methanolation etc [5], though, thermochemical energy storage systems are not yet commercialized. More research and development are needed to better understand the chemistry and resolve practical problems before industrial implementation [9].

Novel and practical methods to store solar thermal energy, with the ability to overcome aforementioned barriers, need to be developed. AD (Anaerobic digestion), a biological conversion process that is effective at converting wet organic wastes into methane biogas and alleviating the environmental concerns associated with waste handling, could be a biochemical option for solar thermal energy storage [10,11]. In the late 1970s, U.S. Environmental Protection Agency (U.S. EPA) first developed a solar powered anaerobic digestion system to improve thermal efficiency of the digestion [12]. Since then, several studies were conducted and focused on further improving the thermal efficiency of anaerobic digestion. Hills and Stephens studied the feasibility of using solar energy to heat a mesophilic CSTR (continuous stirred-tank reactor) anaerobic digester [13]. Alkhamis and his colleagues designed and operated a lab scale digester with a flat plate solar collector as the heater in Jordan [14]. Axaopoulos et al. developed a mathematical model for the simulation of a swine manure reactor heated with solar energy [15]. However, using anaerobic digestion as an energy storage unit to store solar energy has not been comprehensively and thoroughly studied to date [16].

Therefore, the objectives of this study were to investigate a solar-bioreactor system with different digestion operations (manure digestion and co-digestion), and optimize the system to maximize both system efficiency and solar energy storage efficiency. The studied system includes an evacuated solar thermal collector, a heat exchanger, an anaerobic digester, and biogas storage tank (Fig. 1). The solar thermal collector first converts solar radiation into thermal heat to warm up the in-coming organic waste streams and maintain the reactor temperature. The anaerobic reactor at the preferred reaction temperature then converts organic wastes into methane biogas and maximizes the net energy output. The optimized solar-bioreactor system could provide a solution to overcome the disadvantages of individual unit operations such as unsteady energy flow of solar thermal collectors, expensive and complex solar thermal energy storage, and the unfavorable energy balance of anaerobic digestion (particularly for small scale operations).

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