A Review of Solar Energy Use in Biogas Digester Heating

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Abstract: Several factors affect biogas fermentation, among which the temperature fluctuation is crucial. Domestic and foreign biogas fermentation heating systems are also diverse. Among various exist methods of heating biogas fermentation, solar biogas fermentation heating systems are also diverse. The current study reviewed various solar-heating biogas fermentation systems at home and abroad, describing the principle of the solar-heating system, the collector, the heat storage material and the research and application progress. It briefly discussed its characteristics, summarising the critical technology of solar biogas heating systems.

Keywords: Solar energy, Biogas, Fermentation assisted, Thermal storage materials.

1. INTRODUCTION

In recent years, the energy demand has been increasing daily with the rapid development of the economy and society and the improvement of people's living standards. Simultaneously, the alarming environmental pollution is aggravating, and the development of high carbon energy is on the verge of exhaustion. Therefore, how to rationally use energy and develop renewable energy has become a critical research topic in the 21st century [1]. New and renewable energy resources are rich, widely distributed, have considerable development potential [2] and are environmentally friendly. It is critical to protect the ecological environment and take the road of sustainable economic and social development to develop new and renewable energy, especially to convert it into high-grade energy and gradually reduce and replace fossil energy use according to local conditions [3].

Biomass is widely used in numerous renewable energy sources, and biomass-based biofuel production has emerged as a practical approach to enable energy independence, reduce greenhouse gas emissions, revitalise rural communities and enhance sustainable economic development [4]. Biomass energy refers to the energy that is fixed and stored in living things after converting solar energy directly or indirectly into chemical energy through the photosynthesis of green plants. Green plants use chlorophyll to convert CO_2 and H_2O in the air through photosynthesis into glucose and store sunlight light energy. The glucose is polymerised into starch, cellulose, hemicellulose, lignin and other polysaccharides and constitutes organisms. Biomass energy is the only energy that has fossil fuel properties and has the characteristics of storage, transportation, regeneration and conversion and is less restricted by natural conditions.

Biogas fermentation (BF) is a frequently used biomass energy method and the most environmentally friendly and economical way to use biomass energy. BF is where organic matter generates mixed gases, such as methane and CO_2, by catabolising various microorganisms under specific conditions [5]. Raw materials from BF are primarily agricultural and forestry waste (corn straw, livestock and poultry faeces), dead leaves, municipal and industrial organic solid waste (sugar mill residues and wood processing scraps), sewage wastewater (domestic wastewater, slaughterhouse wastewater and tofu wastewater) and household garbage (kitchen garbage).

Methane is one of the main BF products, and biogas is used for living, lighting, cooking and power generation. Furthermore, BF products include biogas slurry and residue, both high-quality organic fertilisers [6, 7]. BF is a closed process. Most harmful substances, such as antibiotics and pathogenic bacteria eggs, have been destroyed; therefore, biogas slurry and residue as fertilisers are environmentally friendly. It can improve the soil and crop quality and prevent crop pests and diseases. In short, BF can reduce fossil energy consumption and greenhouse gas emissions, which have excellent environmental and economic benefits and are critical to sustainable development [8, 9].

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However, developing BF technology faces many challenges, and several factors affect BF. Temperature is critical in the anaerobic biomass digestion process. Excessive temperature fluctuations will affect the metabolic activities of microorganisms in BF, affecting the gas production efficiency [10, 11]. Relevant experiments show that the biogas digester (BD) stops producing gas when the fermentation temperature is lower than 10°C. BF is normal when the BD temperature is above 15°C. If the temperature is too low, the BD will freeze and crack [12, 13]. It is challenging to maintain a suitable temperature for BF in alpine areas, and it is uneconomical to use electricity, petroleum and firewood to heat the BD to maintain it at an ideal temperature [14, 16].

Solar energy is an ideal pollution-free, noise-free and inexhaustible renewable energy source. Solar energy use and conversion technologies have been widely developed over the last several decades [17-19]. Solar photovoltaic and photothermal technologies are rapidly developing globally; therefore, it is advantageous to combine solar energy and biogas, two environment-friendly energy sources, with complementary advantages [20]. Many scholars at home and abroad have researched the combination of solar energy and BF technology.

This study primarily classified the solar-assisted heating biogas fermentation systems globally and explained the heating principle and characteristics of various systems, prospecting and summarising the development of solar-assisted heating systems, the details are as follows:

1. Described various solar assisted heating BFSs in the world.

2. Comprehensively compared the various solar biogas fermentation systems (SBFSs).

3. Reviewed the thermal storage materials for BDs.

4. Proposed the conclusions and prospects of biogas fermentation systems (BFSs).

2. SOLAR-ASSISTED HEATING BFSS

According to solar energy use, applying solar energy in BF heating can be divided into passive solar greenhouse, active solar-heating, solar and other energy-combined heating systems. Figure **1** summarised and classified standard solar-heating BFSs.

2.1. Passive Solar-Assisted Heating BFSs

Passive solar greenhouse uses solar energy to provide indoor heat without other devices to actively collect solar energy or energy to raise indoor temperature. It relies on the natural heat transfer of conduction, convection and radiation. It collects, stores and distributes solar energy effectively through the layout, internal and external structures and material selection of buildings, increasing the temperature and

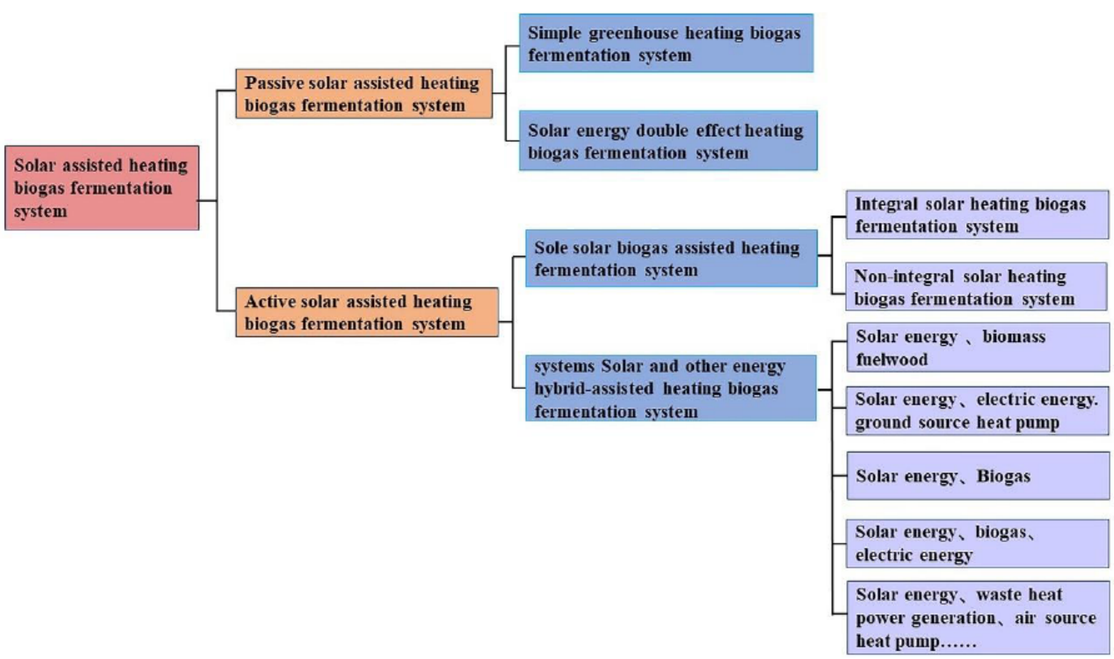

Figure 1: Classification of solar-assisted heating BFSs.

light, providing a warm and bright environment, *i.e*. using the greenhouse effect principle to increase the temperature in buildings [21, 22]. The solar greenhouse effect has many applications in biomass fermentation heating.

2.1.1. Simple Solar Greenhouse-Heating BFSs

In the simple solar greenhouse-heating BFS, the BF tank is directly built in the greenhouse (Figure **2**). Greenhouses absorb solar energy through the greenhouse effect principle, *i.e*. when the short-wave solar radiation enters the room through a sunlight plate with high transmittance, it becomes long-wave radiation after being reflected from the ground. Because greenhouses block long-wave radiation, copious long-wave radiation is absorbed by the air in the greenhouse and the indoor temperature rises [23]. When the ambient temperature in the greenhouse increases to a specific temperature, the fermentation liquid in the BD absorbs heat through the tank wall, and the temperature keeps rising [23-25].

Figure **3** shows northern China's four-in-one model. Greenhouses, toilets, livestock and poultry houses are built together, and BD are built under the livestock and poultry houses. The feeding room is connected to the toilet and livestock and poultry manure tanks, and the discharge mouth extend into the greenhouse [25]. In this way, the excrement of people, livestock and poultry can be directly transferred into the BF tank, and the residual residue and biogas slurry after BF can be directly fertilised for crops. The BF tank and a greenhouse are integrated, and the greenhouse provides heat for the BD. Simultaneously, the BF residue promoted the green production of greenhouse crops [26-28]. Managing this production mode is extensive, significantly reducing labour and financial resources, providing fertiliser for greenhouse production and purifying the environment.

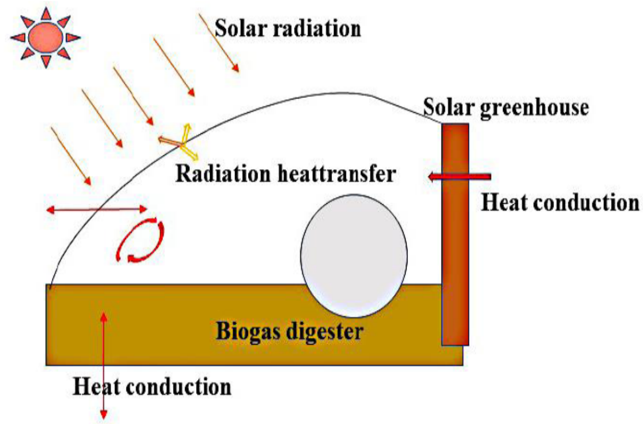

Figure 2: Schematic of the heat transfer in a solar greenhouse [23].

2.1.2. Solar Energy Dual-Effect Heating BFSs

The solar dual-effect heating system refers to BF divided into two stages: acid and methane production. The acid production stage requires a higher temperature, whereas methane production requires a moderately low temperature [29]. Therefore, the solar biogas digester (SBD) is designed to separate the acid and methane fermentation rooms for auxiliary heating. The dual-effect heating system comprise a solar greenhouse and heat-collecting chamber (Figure **4**) [30]. The solar greenhouse comprised a steel frame and a hollow solar panel as the first heating system,

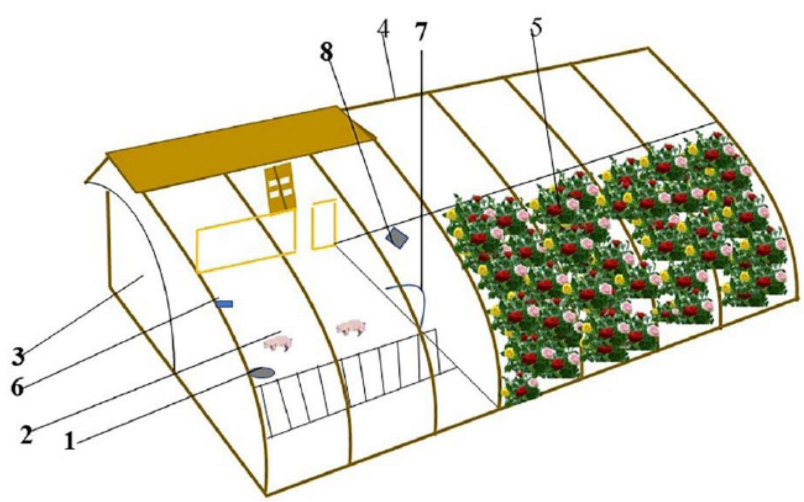

Figure 3: Northern China's four-in-one model.

(1-Biogas digester, 2-Pigsty, 3-One original house, 4-Solar greenhouse, 5-Vegetable field, 6-Feed outlet, 7-Discharge outlet, 8-Air vent).

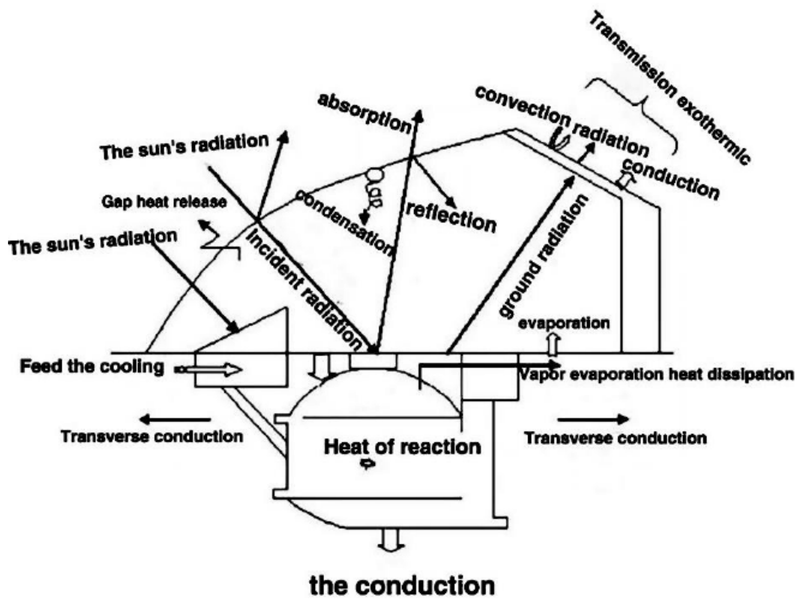

Figure 4: Solar two-calefacient effects on biogas digester in daytime [29].

and the solar heat collection chamber contains a vacuum solar panel and an acidifying pool group as the second heating system. Due to the greenhouse effect, the temperature in the fermentation tank is increased in the first heating system, and the acidification tank absorbs solar radiation energy directly to heat the BF liquid [31, 32]. This two-stage heating system has a double-layer insulation effect. Because of the problem of the different temperatures required by the two stages of acid and methane production, it is more effective to use solar energy by separating the two heating stages.

2.1.3. Characteristics of a Passive Solar-Heating BD and Points Requiring Attention in Construction

The passive solar-heating BFS has a low-energy consumption and can meet the temperature requirements of the BF temperature when sunlight is sufficient. Combining biogas and agricultural production has excellent ecological and economic effects [33]; however, its stability is poor due to the significant influence of solar radiation's change. This method for heating the BD requires a significant initial investment in a heat storage system. In constructing a passive solar-heating BF tank due to seasonal changes and the change in the sun's height angle system, the best orientation must be considered, and the solar greenhouse's insulation is crucial. The ground temperature should be cut off if the digester is built underground. Greenhouse sunlight boards choose a high transmittance to improve solar energy's thermal efficiency.

2.2. Active Solar-Assisted Heating BFSs

Active solar-heating technology uses external technology to collect and use solar energy [34]. Active solar BD can be divided into single SBFs and solar and other hybrid energy-heating systems.

2.2.1. The BFSs of Heating Only Using Solar

Many types of single solar BD exist according to construction methods, heat storage materials and collectors, but most are similar. The single solar-heating system (S-HS) shown in Figure **5** comprises a solar heat collection device, a BF device and a heat storage device. Its working principle is as follows. When the solar heat is sufficient or the outdoor

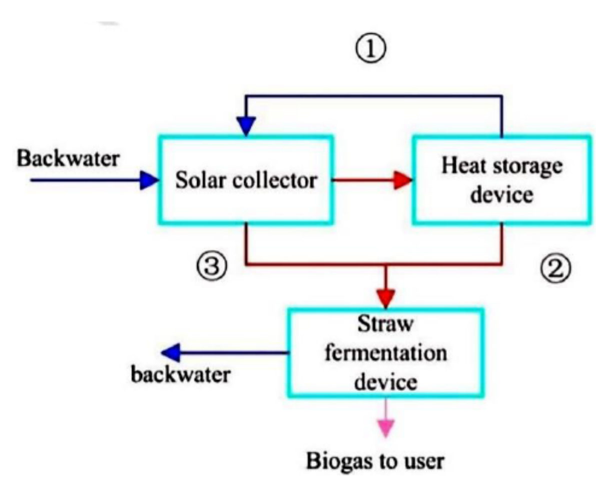

Figure 5: Schematic of solar-heated biogas system with a phase-change material storage tank [35].

temperature is high enough to meet the BF requirements, the heat storage device will store too much solar energy. When there is no sun at night and the digester must be heated, the heat storage device directly provides heat for the digester. When it is cloudy or the sun is not enough, the heat collected cannot meet the BD's heat demand, and the heat storage device and the collector together provide heat for the BD [35-37]. The following will introduce several standard single solar-heating BDs.

2.2.2. Integral Solar-Assisted Heating BFSs

The integral SBD is the entire solar collector and fermentation tank, and part of the BD wall comprises solar collectors. When sunlight shines on the collector, it absorbs solar energy to raise the wall temperature and directly heats the BF feed liquid (Figure **6**) [38, 39].

The integrated SBD has a simple structure and a small footprint. It is easy to use and does not need other auxiliary energies; however, the temperature will lag, and the BD's heating effect in the daytime needs a day to reflect [40]. The collector cost is high (if it is a concentrated collector), the tank's temperature is stratified, and the temperature in each layer of the BD is unevenly distributed. Therefore, to reduce the temperature lag time, the solar collector's area must be increased appropriately, and the solar collector's inclination angle must be changed. Constructing the integrated SBD requires special consideration for insulation and moisture protection; otherwise, the warming effect will not be achieved.

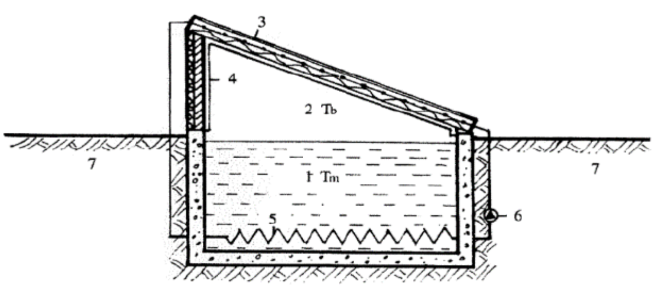

Figure 6: Diagram of the solar-assisted anaerobic digester [38].

(1-Manure, 2-Enclosed biogas, 3-Solar collectors, 4-Plastic cover, 5-Heat exchanger, 6-Pump, 7-Ground).

2.2.3. Non-Integral Single Solar-Assisted-Heating BFSs

This study introduced several standard non-integral solar-heating BFS. Figure **7** shows a single S-HS designed by Karimov K S (2012), comprising an arc solar reflector and a BF device. An arc solar mirror was installed at the bottom of the BF device, and the bottom space was sealed with glass. When sunlight shines on the arced mirror, it will be reflected to the fermentation tank's bottom, absorbing solar energy to heat the fermentation liquid [41]. This heating device is simple in structure but does not have heat storage and preservation systems. BF is unstable and requires excellent heat absorption at the fermenter's bottom.

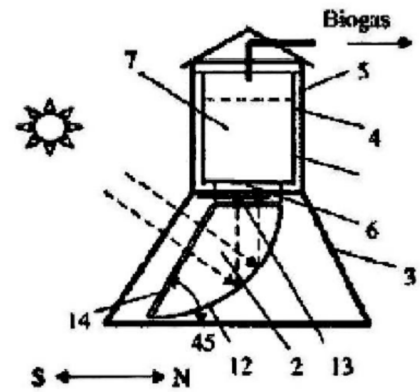

Figure 7: Solar mirrors are installed at the bottom of the BD [41].

(1-Fermentation tank, 2-Reflection and absorption heater, 3-Tripod, 4-Insulation layer, 5-Aluminium foil, 6-Metal absorber, 7-Biogas slurry, 8-Entrance, 9-Exit, 10-Switch, 11-Isolator, 12-Arc, 13-Horizontal glass cover, 14-Inclined glass cover).

Figure **8** shows the vacuum tube S-HS designed by Yu Y Y (2014). The vacuum tube collector collects the water in the solar-heating tube. When the BD must be heated, the water pump sends the hot water into the pipe and heats the fermentation liquid through the heat exchanger laid in the BF tank [42]. Simultaneously, the device is equipped with a heat storage tank, with water as the heat storage material to stabilise the system (Figure **9**).

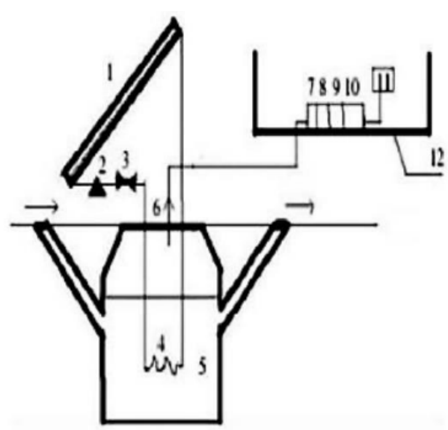

Figure 8: Diagram of solar-assisted-heating BD system [42].

(1-Solar collector, 2-Water pump, 3-Control valve, 4-Heat exchanger, 5-Biogas digester, 6- BD cover, 7-Dehydrator, 8-Pressure gauge, 9-The H_2S processor, 10-Gas counter, 11-Gas stove, 12-The kitchen).

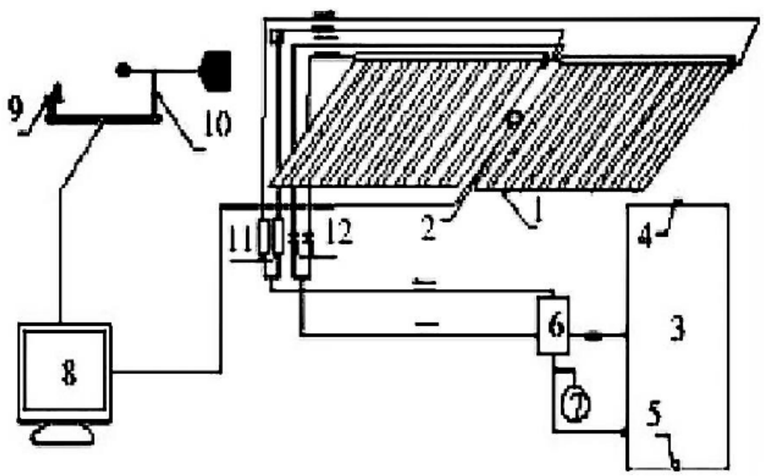

Figure 9: Vacuum tube collector system [42].

(1-Solar collector, 2-Total radiation table, 3-Heat storage water tank, 4-Safety valve, 5-Drain valve, 6-Solar station, 7-Expansion tank, 8-Solar testing system, 9-Anemograph, 10-Wind indicator, 11-Flowmeter, 12-The valve).

The flat-plate solar-collector-heating BF device was used in Alvarez's (2016) experiment. The principle is similar to the above vacuum tube solar-heating biogas device, but it has no heat storage device, and the drop in night temperatures will significantly affect biogas production [43]. Andreas (2016) designed a flat-plate solar-collector-heating anaerobic filter (AF) system (Figure **10**), in which AF reacted to a cylindrical metal container with a double-wall shell and the circulating liquid was a mixture of water and glycol. The flat-plate collector absorbs the mixture of solar-heating in the hot water storage tank and mixes the hot liquid in the storage tank and the circulating liquid in the reactor appropriately by controlling the three-way valve [44]. The mixture is then pumped into the AF reactor's double walls at a set temperature to heat the BF stock. This system's circulating medium is an ethylene glycol mixture to avoid pipe freezing when the temperature is below 0°C.

The heat pipe vacuum tube solar-heating BFS designed by Jiao Y Z (2016), Du S L *et al* (2013) (Figure **11**). The heat pipe exchange tube is in the biogas tank, and the heat pipe collector absorbs solar energy to heat the circulating water. The high-temperature circulating water heats the fermentation liquid through the heat exchanger, and methanol is the heat pipe's working medium [45, 46]. In addition to these single S-HS, some BF heating systems convert solar energy first into electricity, then electricity into heat energy [47, 48].

2.3. Solar and other Energy Hybrid-Assisted-Heating BFSs

Solar and other energy-heating systems make up for the discontinuity of the single S-HS to prevent the adverse impact on BF at night or when there is no

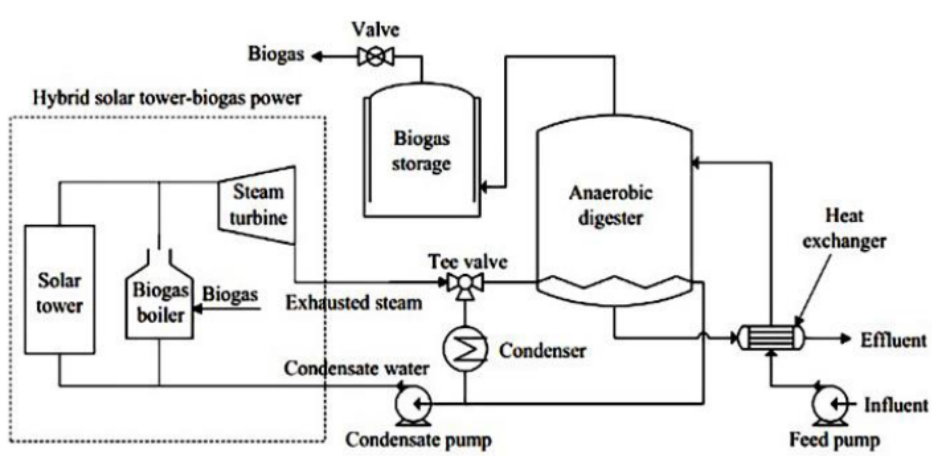

Figure 10: Diagram of biogas production system [44].

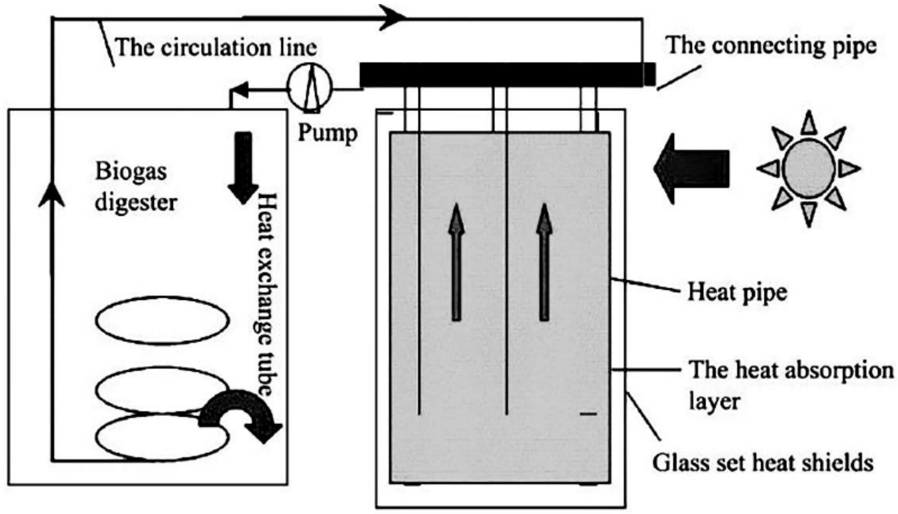

Figure 11: Anaerobic fermentation system with solar energy heat pipe heating [45].

sunlight. Some standard solar and other energy hybrid heating systems are discussed below.

2.3.1. Solar Greenhouse, Biomass Fuel Wood Combined Heating Systems

Fan Z S *et al*. (2006) designed the auxiliary heating container type biogas engineering technology. The BF tank is built inside a solar greenhouse, and the biogas digester's wall is coated with a special high absorption black-coated layer, which can continuously absorb solar energy to improve the fermentation liquid's temperature. The biomass-assisted heating system is initiated to ensure normal BF when the absorbed solar energy cannot meet the requirements. Figure **12** shows the biomass auxiliary heating equipment. Its working principle is that the circulating water pump will suck fresh biogas slurry filtered from the discharge room into the heating water sandwich of the biomass heating furnace. Then, the heated biogas slurry is sent into the BF tank through the pipeline, forming the internal and external circulation of the biogas slurry of the assisted heating, stirring the BF liquid [49].

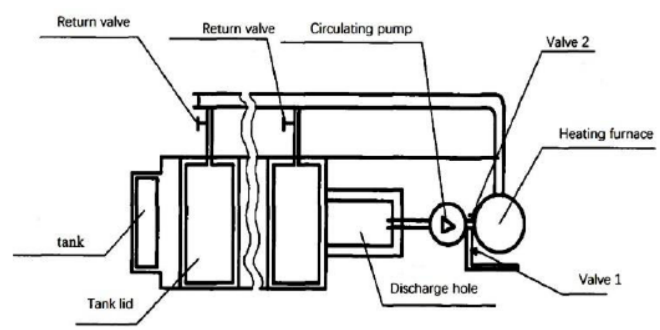

Figure 12: Solar-assisted heating system [49].

2.3.2. Solar Energy and Biogas Combined Heating Systems

Figure **13** shows the solar energy-heating system combined with a biogas boiler Z J H（2008). The solar

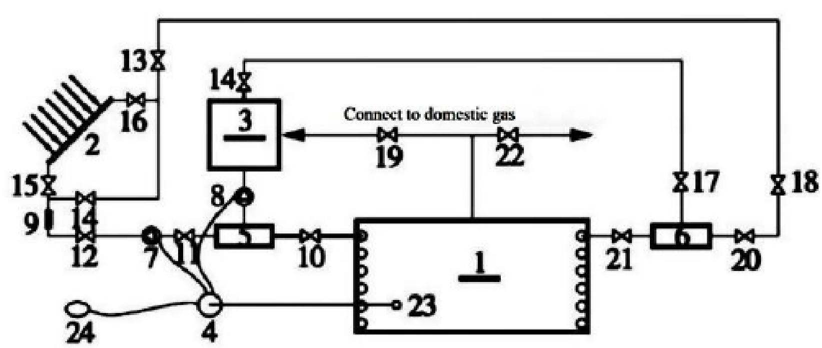

Figure 13: Sketch of solar energy and marsh gas boiler-combined warming system [50].

(1-Biogas digester, 2-Solar collector, 3-Biogas boiler, 4-Water pump controller 5-Water separator, 6-Water collector, 7,8-Circulating water pump, 9-Liquid flowmeter, 10–22-Valve, 23-Temperature sensor, 24-Radiation sensor connected to domestic gas).

and biogas boiler heating systems are connected in parallel. The temperature control equipment is set in the system to monitor the ambient temperature and the BF material and liquid temperature. The system's circulating medium is water [50]. Considering the economy, the preferred heating system is solar energy. If the heat provided by the S-HS cannot meet the requirements of BF, biogas boiler heating or biogas boiler auxiliary heating is used. This system can control the temperature fluctuation of BF liquid within 3°C, ensuring the temperature of BF.

2.3.3. Solar and Electric Energy-Combined Heating System

Li J R (2008) designed the heating system of solar power cooperative inversion (Figure **14**). The solar collector absorbs the solar to heat water, and the water flows into the circulating water tank. When the water temperature in the circulating tank reaches the required level, the control valve is opened, and hot water flows into the heat storage tank. The heat storage tank's hot water transfers heat through the pipeline to the fermentation liquid material, satisfying the temperature conditions of BF. The cold water flows back to the solar collector after heat exchange by a pressurising device and a water pump [51]. Simultaneously, the system adds an electric heater to the circulating water tank for backup to adapt to extraordinary weather conditions. As shown in Figure **15**, the design by El-Mashad (2004) uses a combined solar and electric heating system, but there is a pump chamber, and a heat recovery device is added to collect the pump's wasted heat. Furthermore, the entire system's heat loss is reduced within a heat collection hood, increasing BF reliability [52].

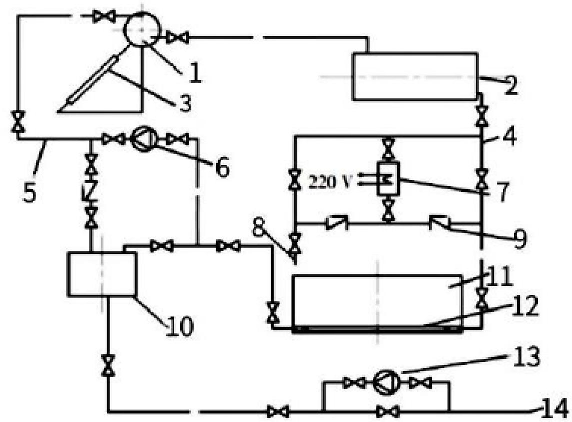

Figure 14: Thermal system of the solar energy BD [51].

(1-Circulating water tank, 2-Heat storage water tank, 3-Solar panels, 4-Heating the water, 5-Filling water, 6-Circulating water pump, 7-Auxiliary heater, 8-Domestic water, 9-The check valve, 11-Biogas digester, 12-Heat exchanger, 10-Supply water device, 13-Tap water pressure pump, 14-Tap water).

2.3.4. Solar Energy, Ground-Source Heat Pump Combined Heating System

Shi H X (2001) designed the combined solar energy and ground-source heat pump (GSHP) heating system (Figure **16**). The GSHP is a new energy use technology that uses shallow geothermal energy for heating and cooling and transfers cold quantity and heat through the Carnot cycle and reverse Carnot cycle principles [53]. The solar collector and the GSHP mutually heat the water and store thermal energy in one hot water storage tank, which then heats the BD through a hot

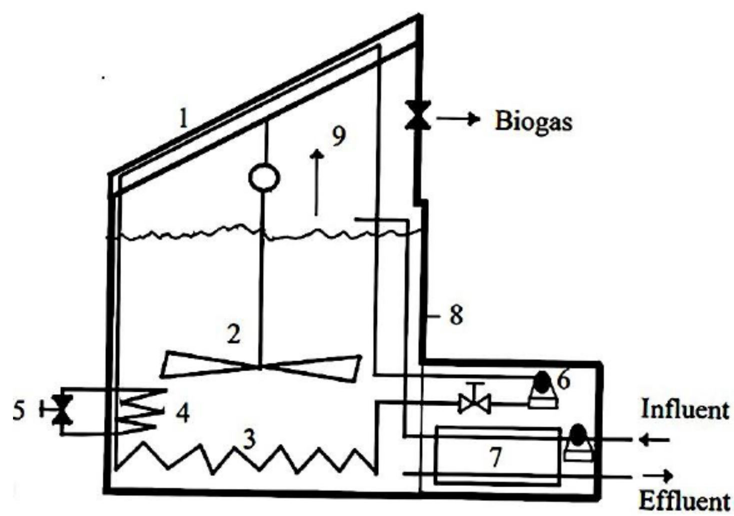

Figure 15: A schematic of the system's configuration [52].

(1-Solar collector, 2-Agitator, 3-Heat exchanger, 4-Auxiliary heater, 5-Control 6-Pump, 7-Heat recovery unit, 8-Insulating cover, 9-Extra gas volume).

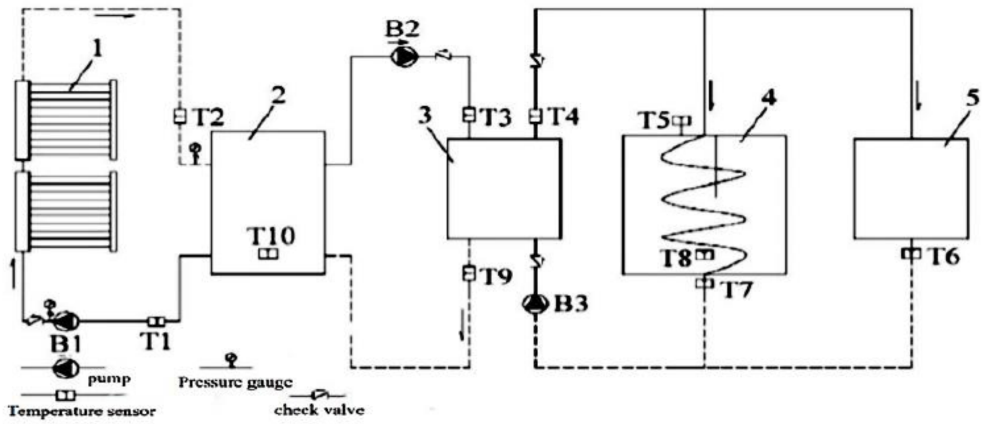

Figure 16: Solar-assisted heat pump-based heating system of the biogas project [53].
(1-Solar collector, 2-Hot water storage tank, 3-Heat pump unit, 4-BD 5-Office area).

water cycle [54-56]. A GSHP uses electricity to extract geothermal energy, *i.e*. solar energy and electricity heating.

2.3.5. Multi-Energy-Combined Heating System

Various energy-combined heating systems exist. For example, the solar energy, biogas and electric energy-heating system, the solar energy collection, air source heat pump and electric heating parallel-biogas fermentation heating system, and the solar energy collection, air source heat pump and power generation waste heat parallel-biogas fermentation heating system [57-59]. In addition to the above, biogas and solar energy are mixed to generate electricity, and biogas is heated and fermented using the waste heat from power generation [60, 61].

2.4. Conclusion of the S-HSs

From the above, all S-HSs have their own characteristics (Figure **17**). The most significant characteristic of passive solar energy is its low cost and ease of operation and management. However, due to the discontinuity of solar energy, a significant temperature difference between day and night makes the system less stable. The cost of single solar energy in an active solar system is medium, and the operation and management are convenient, but the system is unstable. The combined solar and other energy-heating system is expensive, has a complex operation and management and requires other energy consumption, but it has excellent stability to meet the temperature required for BF all year round. Furthermore, all S-HSs are environmentally friendly.

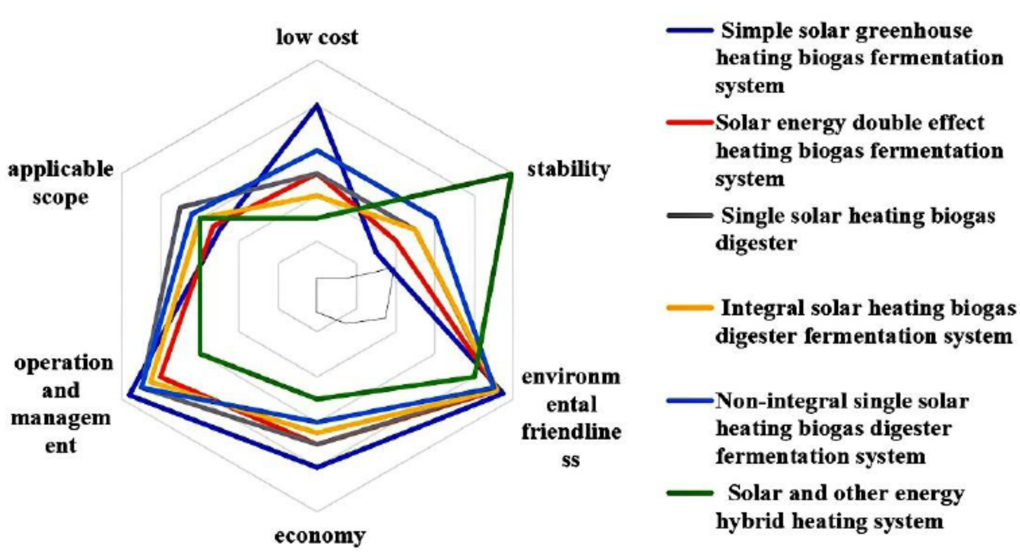

Figure 17: Comprehensive comparison.

3. THERMAL STORAGE MATERIALS FOR BDS

Insulation is necessary for active and passive S-HSs, and heat storage materials are crucial for heat storage systems. The following is a brief overview of the heat storage materials in S-HSs.

A heat storage device collects excess heat when solar energy resources are substantial. Furthermore, the BD continues to be heated to ensure the temperature and continuity of BF when solar energy resources are insufficient or there is no sunlight. The heat storage device transfers the surplus solar energy resources when the solar energy resources are weak. It can effectively use the solar energy resources and buffer their impact during changes in the weather and day and night temperature fluctuations to better promote solar energy resource use. The heat storage materials in the heat storage device for the BD can be divided into sensible and latent heat storage materials according to the heat storage method.

3.1. Sensible Heat Thermal Storage Materials

Sensible heat storage without changing the material state stores heat by increasing the temperature of the heat storage material. Common heat storage materials include gravel, brick, concrete, water, ethanol and butanol. Water is used broadly as a heat storage material because of its wide temperature range and low price [62, 63]. However, glycol and molten salt are sometimes used for heat storage in solar-heating BFSs [64-66].

3.2. Latent Heat Thermal Storage Materials

Latent heat materials can absorb or release heat during phase transformation, and the latent heat of the materials is larger than sensible heat storage, and their volume is smaller [67]. Common latent heat storage materials include paraffin, fluoride and organic alcohol. Paraffin is the most used material in solar-heating BF systems because of its high energy storage density, wide-phase transition temperature, small-phase transition volume, easily obtainable and other characteristics [68] .

4. CONCLUSIONS AND PROSPECTS

In the solar energy gas heating system, passive solar-heating is the most convenient and lowest cost management, but its stability is poor. Active solar energy-combined with other energy-heating methods is the most widely used. Only the combination of solar energy and other energy sources can ensure that the temperature of BF does not fluctuate significantly throughout the day. The S-HS must focus on promoting, researching and developing low-energy-heating and insulation technology, promoting process improvement, reducing non-renewable energy use and attaching importance to developing and using multi-function complementary modes. Furthermore, due to the local climate conditions, the S-HSs and collectors, the size of the heat collection area and angle must be selected according to local conditions. In short, the solar-heating BFS has excellent application prospects, critical for environmental protection and improving people's quality of life. Combining solar and biomass energy with complementary advantages can promote the sustainable development of biogas projects in cold areas.

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