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A self-sustaining high-strength wastewater treatment system using solar-bio-hybrid power generation

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HIGHLIGHTS

- Solar- and bio-technologies were combined for a new wastewater treatment concept.
- CSP- and PV-bio hybrid solutions were compared to power the treatment.
- Integrating PV, AD and AET is a preferred solution of the self-sustaining treatment.

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ABSTRACT

This study focuses on system analysis of a self-sustaining high-strength wastewater treatment concept combining solar technologies, anaerobic digestion, and aerobic treatment to reclaim water. A solar bio-hybrid power generation unit was adopted to power the wastewater treatment. Concentrated solar power (CSP) and photovoltaics (PV) were combined with biogas energy from anaerobic digestion. Biogas is also used to store the extra energy generated by the hybrid power unit and ensure stable and continuous wastewater treatment. It was determined from the energy balance analysis that the PV-bio hybrid power unit is the preferred energy unit to realize the self-sustaining high-strength wastewater treatment. With short-term solar energy storage, the PV-bio-hybrid power unit in Phoenix, AZ requires solar collection area (4032 m^2) and biogas storage (35 m^3), while the same unit in Lansing, MI needs bigger solar collection area and biogas storage (5821 m^2 and 105 m^3, respectively) due to the cold climate.

1. Introduction

The United Nations Environment Program (UNEP) reported that two billion tons of sewage, industrial and agricultural wastewater are discharged into the world's waterways every day (UNEP et al., 2010). A significant amount of them is high strength wastewater defined as the wastewater with elevated levels of organics (Mutamim et al., 2012), such as wastewater from animal farms and food processing facilities. The wastewater has affected approximately 245000 km^2 of marine ecosystems (UNEP et al., 2010), and methane and nitrous oxide from the degradation of organic matter in the wastewater greatly contribute to global greenhouse gas emissions. On the other hand, the wastewater, particularly high-strength wastewater, is rich in organic matter, which represents a good carbon and nutrient (phosphorus and nitrogen) source for microbes to synthesize energy and chemical products. However, fecal matters and low-concentration nutrients in the wastewater present technical challenges to utilize them for energy and chemical production. New scientific and engineering solutions are urgently needed to address these challenges and transform the wastewater from a major environmental and health hazard into a clean and attractive resource.

Current wastewater treatment technologies mainly rely on aerobic treatment (AET) in which microbes aerobically degrade the soluble and colloidal organics and reclaim the water (Speece, 1996). However, due to the aeration, AET is an energy-intensive operation with a relatively large carbon footprint from fossil energy consumption (US-EPA, 2010). For high-strength wastewater treatment, a much larger carbon footprint is required considering the fact that aerobic microbes require more oxygen and longer retention. Therefore, carbon neutral and self-sustaining system needs to be developed for next-generation wastewater treatment. Compared to conventional AET, anaerobic digestion (AD) is another biological means that is able to simultaneously treat high-strength

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wastewater and generate bioenergy, and has the potential to be further developed into a carbon neutral process (Sun et al., 2015). However, due to the microbial community structure and their metabolic pathways, the growth of anaerobic microbes is much slower than aerobic microbes (Speece, 1996; Ye and Zhang, 2013), so that the nutrient removal of AD is not very efficient, and the wastewater cannot be reclaimed completely (Speece, 1996). It has been demonstrated that integrating anaerobic and aerobic processes to treat wastewater is an effective approach to take advantages of both systems (i.e., AD's capability of handling high-strength wastewater and its energy production, and AET's efficient nutrient removal) (Chan et al., 2009). It can thus be used to completely reclaim water from a wide range of organic wastewater streams (Deshpande et al., 2012; Martin et al., 2011; Novak et al., 2011; Zhou et al., 2015). Although the AD in the integrated system can provide a certain amount of energy to support the operations, the system including biogas cleaning and upgrading, AD, and AET demands more energy than can be provided by the biogas energy of the AD. Additional energy sources are required to achieve a self-sustaining wastewater treatment.

In response to this need, solar energy could be the additional renewable source to satisfy the energy demand. Solar energy was first studied by U.S. Environmental Protection Agency (U.S. EPA) in the later 1970s as the heat source to improve thermal efficiency of anaerobic digestion (Malcolm and Cassel, 1978). Since then, many studies have been conducted on this topic. Hills and Stephens conducted the feasibility of using solar energy to heat a mesophilic continuous stirred-tank reactor (CSTR) anaerobic digester (Hills and Stephens, 1980). Axaopoulos et al. developed a simulation model for a swine manure reactor heated by solar energy (Axaopoulos et al., 2001). Alvarez et al. studied the integration of solar heat, thermophilic anaerobic digestion, and constructed treatment wetland to treat wastewater and enhance biogas production (Alvarez et al., 2016). However, integrating solar power, anaerobic digestion, and aerobic process to treat high-strength wastewater has not been comprehensively studied to date. Therefore, the objectives of this study were to model a solar-bio hybrid wastewater treatment that could self-sustainably reclaim high-strength agricultural wastewater, and to understand the effects of the seasonal and temporal variation (direct normal irradiance and global horizontal irradiance) on the solar-bio hybrid wastewater treatment system. In the past decades, many solar power conversion technologies, such as parabolic trough systems, central tower systems, dish solar systems, Fresnel reflectors, and photovoltaic (PV) cells have been developed (Mills, 2004). They are mainly classified into two categories: solar thermal and electrical (PV) conversion. Both types were studied in this paper. The parabolic trough collector was selected as the solar thermal conversion technology, due to the fact that its temperature is compatible with the steam generation system (<400 °C) (Siva Reddy et al., 2013). In addition, PV cells were investigated as the solar electric conversion technology, considering their simplicity for direct electricity generation.

2. The solar–bio hybrid wastewater treatment system

2.1. Anaerobic digestion (AD)

The simulation of the AD was based on the operational and laboratory data from a commercial anaerobic digester located at Michigan State University (MSU) south campus (42° 41′N, 84° 29′W) in 2015. Animal manure, food waste and FOG (fat, oil, and grease) were the feedstock. The animal manure was from the MSU dairy farm. The animal feed of the dairy farm consisted of alfalfa and corn silage blended according to the National Research Council (NRC)'s standard Total Mixed Rations (TMRs) for dairy cattle. The food waste came from dining halls at MSU campus and local restaurants. The digester is a completely stirred tank reactor (CSTR), operated at a temperature of 40 °C and with a retention time of 20 days. The characteristics of the feedstock are listed in Table 1. The animal manure and food waste were collected in two pits with volumes of 76 m^3 and 95 m^3. The waste in the pits had an average of 8% total solids, and was ground and pumped into a mixing tank (with a volume of 38 m^3). The mixed AD influent was then fed into the digester (with a volume of 1570 m^3). In order to maintain the culture temperature, a heating loop was installed to circulate the hot water continuously from the power generation unit to maintain the temperature of the digester. A double high-density polyethylene (HDPE) membrane covers the top of the digester. The AD effluent was separated by a liquid/solid separator to obtain AD fiber and liquid filtrate. A conveyor moved the wet AD fiber to a storage barn for composting of fertilizer production, and the liquid filtrate was transferred to a tank for the secondary treatment (Fig. 1).

2.2. Biogas upgrading

The mass balance and energy consumption of the biogas upgrading was based on the literature data (Ryckebosch et al., 2011; Sun et al., 2015). The raw biogas was cleaned and upgraded using a two-stage process of water scrubbing and cryogenic separation to remove humidity, CO_2, H_2S, and other chemical compounds. The upgraded biogas was stored in a metallic heavy-duty tank to be used as the fuel for the power generation.

2.3. Aerobic treatment (AET)

After the solid/liquid separation, the AD effluent (filtrate) was further treated by a conventional AET operation (Fig. 1). The simulation of the AET was based on literature data. The filtrate entered into the aeration chamber, where the dissolved oxygen was maintained between 1 and 2 mg/L (EPA, 2000; Wang et al., 2009). The daily operation consisted of two batches (12 h operation time per batch) (Ge et al., 2013). The AET effluent was pumped into a clarifier tank where solids were settled out. The reclaimed water after the clarification, which satisfied the EPA discharging standard, can then be used for other non-potable agricultural applications.

2.4. Solar–bio hybridization of power generation

One of the key criteria for the hybridization power system is that the energy sources of solar and biogas energy must be balanced for a continuous power supply to satisfy the wastewater operation need. The solar collection area (for CSP and PV) must be determined to match the storage needs of biogas for year-round operation.

2.4.1. Solar–thermal–bio hybridization power generation

The solar–bio hybridization is shown in Fig. 2a. The energy requirements (thermal and electrical) of the wastewater treatment

Table 1
Feedstocks of the anaerobic digester.

Description	Total solids (%)	Volatile solids (%)	pH
Animal manure[A]	9.9 ± 1.3	8.3 ± 1.2	7.13 ± 0.98
Food waste[B]	8.5 ± 2.8	7.7 ± 2.4	4.60 ± 0.82
Mixed AD influent[C]	8.5 ± 2.2	7.2 ± 1.9	6.21 ± 0.93

[A] Data are the average of 25 samples with standard deviation.
[B] Data are the average of 24 samples with standard deviation.
[C] Data are the average of 45 samples with standard deviation.

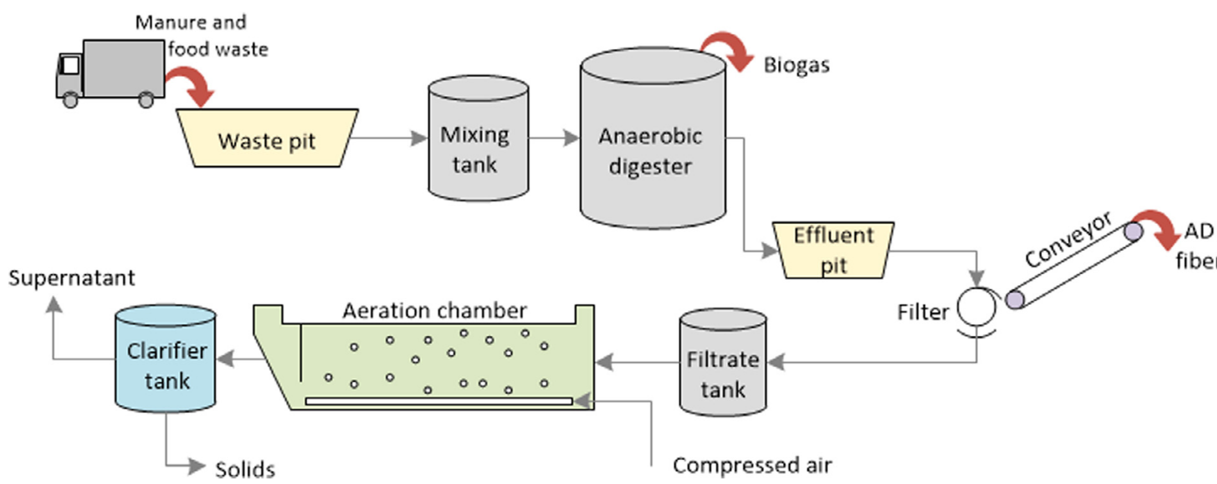


Fig. 1. Flow diagram for a conventional anaerobic/aerobic digestion process.

were provided by steam power generation. A concentrated solar collector (CSP) was installed to collect and transfer solar energy into a heating transfer fluid (HTF) to preheat the feedwater. Two buffer tanks (cold and hot storage) were used to store the collected solar energy to continuously preheat the feedwater. In the case of electricity generation without short-term solar energy storage, the solar heat storage can support the feedwater heating operation for 30 min. In the case of electricity generation with short-term solar energy storage, the size of the hot storage tank is increased to accommodate the heat storage to support the feedwater preheating operation for one day. The preheated feedwater was then sent into the boiler to produce superheated steam using the upgraded biogas as the fuel. The steam was then expanded in the turbine, generating shaft work that was used as an electric generator. The expanded steam was cooled and condensed. The cool water was then returned to the feedwater tank to continue with the cycle. The extracted thermal energy was used to maintain the AD temperature.

The power generator consisted of a 325 kWe steam turbine that was designed to accommodate the use of both biogas and solar energy. The heat input (Q_i^{ref}) required to satisfy the temperature and pressure of the superheated steam, is calculated as:

$$Q_i^{ref} = \frac{P_e}{\eta_e \cdot \eta_*} \tag{1}$$

where η_e is the turbine efficiency (thermal to electrical energy); and η_* is the heat exchanger (η_h) efficiency (set at 0.85), or the fuel-to-steam efficiency (η_b). The thermal energy extracted in the condenser (Q_o) is defined as:

$$Q_o = (Q_i^{ref} \cdot 0.5) \cdot \eta_c \tag{2}$$

where η_c is the condenser efficiency. The parasitic energy required by the power generation system was set at 5% of the designed electricity power output (16.25 kWe), which considers the energy consumed by pumps, gas fans, and miscellaneous equipment for the operation. The parameters for the steam turbine are summarized in Table 2.

A commercial boiler, model CBEX Elite 125 BHP was used to simulate the steam generation (Cleaver-Brooks, 2011). For load capacities of 25%, 50%, 75%, and 100%, the fuel-to-steam efficiencies were 84.2%, 84.7%, 84.6%, and 84.4%, respectively. An average fuel-to-steam efficiency of $\eta_b = 84.48\%$ was considered for the thermal energy input calculation (η_b includes convection and radiation losses, combustion efficiency, heat exchanger efficiency, and 15% excess air in the exhaust flue gas for the selected model).

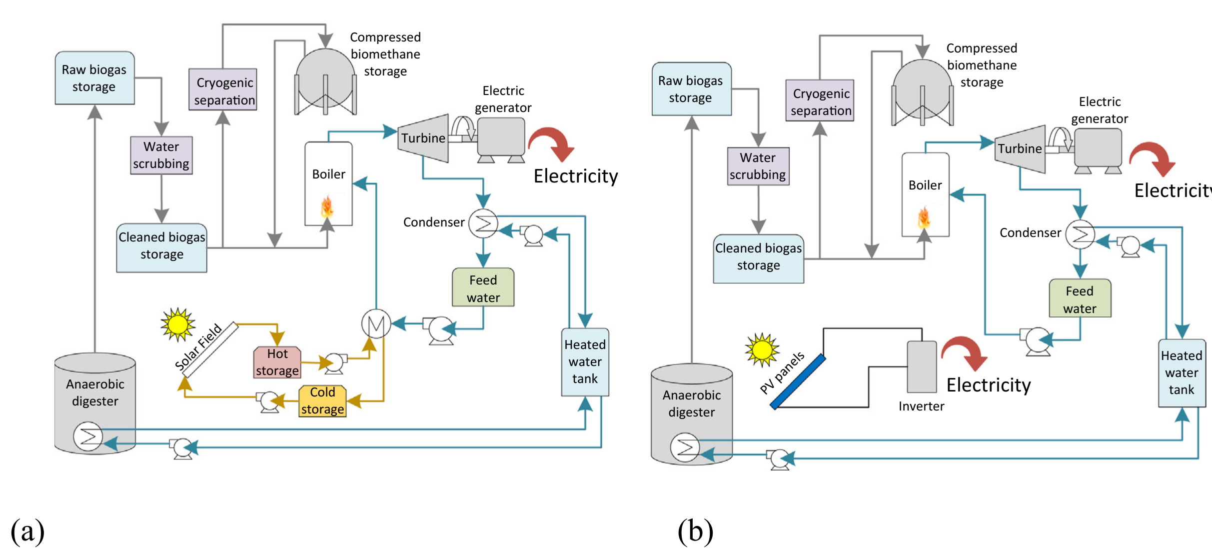


Fig. 2. Components of energy generation combining biogas and solar energy: (a) CSP-bio-hybrid system, (b) PV-bio-hybrid system.

Table 2
Operational parameters of 325 kW steam turbine.

Parameter	Value	Unit
Maximum electricity output	390	kWe
Minimum electricity output	81.25	kWe
Turbine efficiency	0.35	–
Design heat input	928.57	kWt
Maximum heat input	1111.2	kWt
Minimum heat input	275.62	kWt
Thermal energy extracted	464.2	kWt

In addition, the relationship between electricity generation and thermal energy input can be expressed by a polynomial equation (NREL, 2016b) as:

$$P = \left(\beta_0 + \beta_1 \cdot \left(\frac{Q_i}{Q_i^{ref}}\right) + \beta_2 \cdot \left(\frac{Q_i}{Q_i^{ref}}\right)^2 + \beta_3 \cdot \left(\frac{Q_i}{Q_i^{ref}}\right)^3\right) \cdot P_e \quad (3)$$

where P is the electrical power generated (kWe); Q_i is the input thermal energy (kWt); β_{0-3} are coefficients for turbine modeling (−0.0572; 1.0041; 0.1255; −0.0724, respectively). The extracted thermal energy in the condenser can also be defined by the polynomial equation:

$$Q = \left(\beta_0 + \beta_1 \cdot \left(\frac{Q_i}{Q_i^{ref}}\right) + \beta_2 \cdot \left(\frac{Q_i}{Q_i^{ref}}\right)^2 + \beta_3 \cdot \left(\frac{Q_i}{Q_i^{ref}}\right)^3\right) \cdot Q_o \quad (4)$$

Siemens SunField solar collector assembly (SCA) parabolic reflectors (aperture reflecting area 6 m^2, average focal length 1.5 m) were selected as the solar collectors. The heating collection elements (HCE) consist of model 2008 Schott PTR70 vacuum tubes. The optical factors for the SCA and HCE are listed in Table S1.

A single-axis tracing system (the trough is placed from east to west) was used to concentrate solar radiation into vacuum tubes, where synthetic oil (working fluid) absorbed and transferred the thermal energy. The heated synthetic oil was then used to preheat the feedwater before the boiler. Two buffer tanks (hot and cold storage) were used to store the thermal energy and heat the feedwater.

2.4.2. Pv–bio hybridization power generation

The PV-bio hybridization power unit was also studied to supply extra electric energy instead of thermal energy to the wastewater treatment system (Fig. 2b). The analysis was performed by modeling the installation of panels, model SolarWorld SW235 mono, 60 cells per module, 30° tilted, degradation of 0.5% per year, and maximum power of 235 W under reference conditions (cell temperature at 25 °C and 1000 W/m^2 of solar radiation). The System Advisor Model from NREL was used to calculate the nominal operating cell temperature (NOCT), and to quantify the energy generation under different solar radiation values (NREL, 2016b). System losses include losses in the DC and AC energy conversion, such as in the diodes and connections (0.5%), DC wiring (2%), soiling (5%), AC wiring (1%), and transformer (1%). In addition, short-term solar energy storage can be added to extend the operating hours for electricity generation by installing a battery bank, which has a storage capacity that can hold 50% of the maximum daily electricity collection in a year.

2.5. Analytical methods for AD

The methane and carbon dioxide contents of the biogas from MSU anaerobic digester were quantified using a SRI 8610c gas chromatograph (Torrance, CA). The system was equipped with a thermal conductivity detector. The detector was maintained at 150 °C during the analysis. Hydrogen and helium were carrier gases, and maintained at 21 psi. The biogas sample volume was 100 µL, and the syringe was purged three times before sample injection. The chemical oxygen demand (COD), total phosphate (TP) and total nitrogen (TN) of the animal manure and food waste, AD effluent, and liquid filtrate were measured using HACH methods (HACH, 2004). The total solids (TS) and volatile solids (VS) were analyzed using the standard method (APHA, 1998).

3. Results

3.1. Mass balance of the wastewater treatment

A mass balance was conducted to evaluate the system performance. The operational parameters for the anaerobic digester are listed in Table 3. The AD system generated 2919.9 m^3/day of biogas, 11.41 m^3/day of solid digestate (AD fiber), and 64.66 m^3/day of liquid filtrate (Fig. 3) under the conditions of 25 days hydraulic retention time (HRT) and a digestion temperature of 40 °C. The corresponding TS and COD removal were 41% and 62%, respectively. However, there was still a significant quantity of nutrients remaining in the filtrate, particularly TN (4290 mg/L) and TSS (23734 mg/L) (Table S2). Further treatment was needed to reclaim the water for other uses.

The AD filtrate was then treated by the AET process, including an aeration chamber and clarifier tank (Fig. 1). The minimum nutrient removal requirement for secondary treatments (Federation, 2009) as well as the water quality standard for agricultural use (Lazarova and Bahri, 2005) is shown in Table S3. According to these parameters, the total suspended solids (TSS), COD, TP, and TN in the influent of the AET process must be less than 250 mg/L, 400 mg/L, 15 mg/L, and 20 mg/L, respectively. Because the AD filtrate had much higher concentrations than these values (Table S2), it requires a large volume of the aeration chamber (5080.98 m^3) to treat it (Fig. 3). The COD was used as the critical parameter to calculate the required volume. After the AET, the system generated 32.33 m^3 of reclaimed water every 12 h for irrigation uses.

3.2. Energy balance of the solar–bio hybridization wastewater treatment

3.2.1. Electricity demands of the wastewater treatment

Table S4 shows the electricity demand by the AD operation. The electricity usage of the different equipment during the AD operation has been arranged to enable a relatively even distribution of the electricity loading throughout a day, and to improve the engine efficiency. The average electricity demand for the AD operation was 293 kW (Fig. 4).

Table 3
Performance of anaerobic digestion.

Description	Unit	Value
Operating temperature	°C	40
Hydraulic retention time	day	25
Feed pH[A]	–	6.22 ± 0.93
Feed COD[B]	mg/L	133250 ± 21173
Biogas production[C]	m^3/day	2919.9 ± 1643.9
Methane composition	–	0.60
Daily waste feeding	m^3/day	76.07
Liquid filtrate	m^3/day	64.66
Solid digestate (AD fiber)	m^3/day	11.41
Average energy demand for the AD operation	kWh/day	1276

[A] Data is the average of 45 samples with standard deviation.
[B] Data is the average of 8 samples with standard deviation.
[C] Data is the average of 365 samples with standard deviation

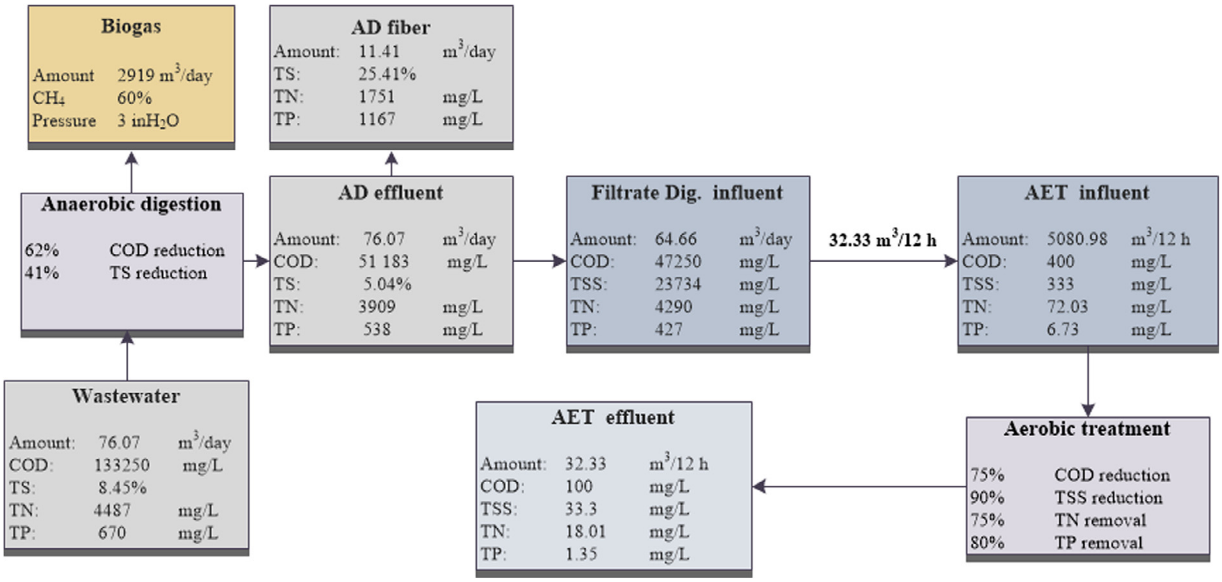


Fig. 3. Mass balance of the integrated anaerobic digestion and aerobic treatment.

The biogas cleaning and upgrading had the highest electricity requirements. It has been reported that the electricity demands of water scrubbing and methane cryogenic separation are $0.275\ kWh/Nm^3_{biogas}$ and $0.35\ kWh/Nm^3_{biogas}$, respectively (Sun et al., 2015). The effect of temperature on normalized biogas volume is expressed as follows:

$$V_N = \frac{P_{AD} \cdot V_B}{T_{AD}} \cdot \frac{T_N}{P_N} \tag{5}$$

where $P_N = 1$ atm; $T_N = 288.15$ K; $P_{AD} = 1.0074$ atm; and $T_{AD} = 308.15$ K. Eq. (5) was then used to calculate the conversion factor between real biogas and normalized biogas. The electricity demands for water scrubbing and cryogenic separation were $1.068\ MJ/m^3_{biogas}$ and $1.359\ MJ/m^3_{biogas}$.

As for the AET operation, it has been reported that the aeration ranges from 3.75 to 15 $m^3_{air}/m^3_{influent}$ in order to maintain the dissolved oxygen concentration between 1 and 2 mg/L (Wang et al., 2009). An intermediate value of 9.375 $m^3_{air}/m^3_{influent}$ was selected by this study to carry out the energy analysis. Since the volume of each AET operation was 5080 m^3 influent each 12 h, the aeration rate needed to be 1.103 m^3 air/s (0.013 m^3 air/m^3 influent per min) to satisfy the required dissolved oxygen concentration. The power for the air compressor can be correspondingly calculated as:

$$P_{comp} = \frac{\alpha \cdot m_{air}}{\eta_{comp}} \tag{6}$$

$$\alpha = \frac{\gamma}{\gamma - 1} \cdot p_0 \cdot \left(\left(\frac{p_1}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \tag{7}$$

where m_{air} is the air flow requirement (m^3_{air}/s); η_{comp} is the compressor efficiency (0.90); γ is the ratio between the specific heat at constant pressure and the specific heat at constant volume ($\gamma = 1.4$); p_0 is the atmospheric pressure (101,000 Pa); and p_1 is the outlet air pressure (303,000 Pa). The compressor requires 159.70 kW to provide the air needed for the process. Fig. 4 indicates that aeration is the largest energy consumer among the unit operations of the wastewater treatment.

3.2.2. Thermal energy requirements of the wastewater treatment

Thermal energy is needed by the anaerobic digestion to heat the feed and maintain the culture temperature at 40 °C. The energy

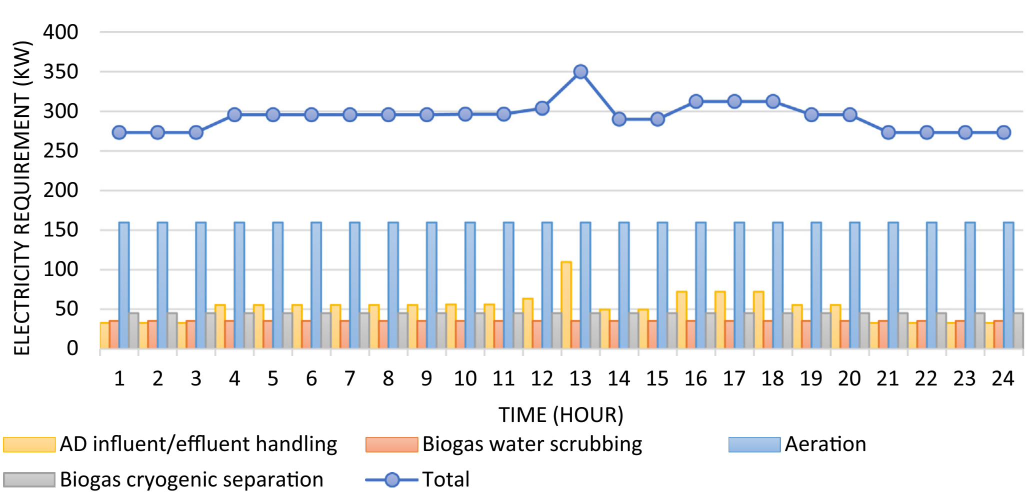


Fig. 4. Daily electricity demands of the wastewater treatment.

requirement per day (E_{req} (MJ/day)) is calculated as (Yue et al., 2013):

$$E_{req} = \frac{V_{AD}}{HRT} \cdot \rho_{inf} \cdot C_p \cdot (T_{AD} - T_{inf}) \cdot (1 + 0.3)/10^6 \quad (8)$$

where V_{AD} is the digester volume (m^3); HRT is the hydraulic retention time (days); ρ_{inf} is the feed density (1220 kg/m^3); C_p is the feed specific heat (4120 J/kg·°C); T_{AD} is the culture temperature (40 °C); T_{inf} is the feed temperature (it is assumed to be the same as the ambient temperature when the ambient temperature is above 4 °C, and it is set at 4 °C when the ambient temperature is below 4 °C); and 0.3 is the additional heat that is needed to maintain the mesophilic culture condition of the digester. Due to the lower atmospheric temperature year-round in Lansing, the thermal energy needed to maintain the AD culture was an average of 323,099 MJ/-month for the operation, which was almost double that in Phoenix (153,182 MJ/month) (Fig. S1).

3.2.3. Energy generation

The studied systems used the AD to generate energy for the wastewater treatment system. However, the electricity (5548.14 kWh/day from the AD on the feed of 76 $m^3_{influent}$ per day) generated is insufficient to cover the energy demand (7032 kWhe/day) of the wastewater treatment system, owing to the high electricity demand of the AET operation. Solar energy was then added into the system as the second energy source.

Since solar energy collection is largely influenced by the geographical location and season, a year-round and hourly-based analysis was carried out at two locations (Lansing, MI (42° 41′N, 84° 29′W) and Phoenix, AZ (33° 26′N, 112° 4′)). These locations represent the low and high annual average direct normal and global irradiation in the United States (7.5–4 kWh/m^2·day and 6.5–3 kWh/m^2·day, respectively) (NREL, 2016a). Fig. S2 shows the variation of solar radiation (Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI)) and ambient temperature during a year for both locations (NREL, 2015). The DNI is the amount of solar radiation received by a surface held perpendicular to the rays that arrive in a straight line from the direction of the sun, which is of particular interest to concentrating solar thermal installations, such as parabolic troughs. GHI is the amount of solar radiation received by a surface horizontal to the ground, including both direct and diffuse solar radiation. GHI is widely used for static collection systems, such as photovoltaic panels. Phoenix has much higher DNI, GHI, and atmospheric temperature than Lansing, while, the ratio of GHI:DNI in Lansing is higher than Phoenix (Fig. S2).

The CSP-bio hybrid power unit uses parabolic trough collectors to collect and transfer solar heat via the HTF to support electricity production (Fig. 2a). The energy loss of HTF can be obtained as

$$Q_p = (\xi_3 \cdot (\bar{T}_{HTF} - T_{amb})^3 + \xi_2 \cdot (\bar{T}_{HTF} - T_{amb})^2 + \xi_1 \cdot (\bar{T}_{HTF} - T_{amb})) \cdot Q_p^{ref} \cdot A_{SCA} \quad (9)$$

where Q_p is the heat loss in the piping system (kW); $\xi_{1,2,3}$ are coefficients (0.001693, -1.68×10^{-5}, 6.78×10^{-8}); $\bar{T}_{HTF}$ is the average temperature of the working fluid for this study (325 °C); T_{amb} is the ambient temperature (°C); Q_p^{ref} is the reference heat loss in the piping system when $\bar{T}_{HTF} = 316.5$ °C (10 W/m^2_{SCA}); and A_{SCA} is the area of the SCA (m^2).

The net thermal energy collected from the SCA (Q_N (kW)) is then calculated as

$$Q_N = \left(DNI \cdot \eta_{op} \cdot A_{SCA}\right) - \left(\frac{Q_{HCE\_L} \cdot A_{SCA}}{1000}\right) - (Q_p) \quad (10)$$

where DNI is the direct normal irradiance (kW/m^2), the optical efficiency (η_{op}) is 0.74 (Table S1), and the heat loss in the HCE has been documented as $Q_{HCE\_L} = 6.609$ W/m^2 for the selected vacuum tube model (NREL, 2016b).

The net heat used for steam generation is obtained as $Q_{ns} = Q_N \cdot \eta_b$. Eq. (3) is used to calculate the electricity generation. The electricity load of the wastewater treatment (Fig. 4) is compared hourly with the electricity generation from the solar–bio hybrid unit. In the hybrid configuration, if the energy amount collected from the DNI is insufficient to satisfy the energy demand to generate the superheated steam for the turbine, biogas is burned to compensate the energy deficiency and generate the superheated steam (Colmenar-Santos et al., 2015; Sun et al., 2015). If the energy quality (temperature) collected from the DNI is higher than the requirement for superheated steam generation, the energy collected in the SCA is then used to preheat the feedwater for the boiler and reduce the biogas demand during the superheated steam generation. Combining biogas and solar energy can synergistically mitigate the issues of unstable solar energy flow and limited biogas production.

The PV-bio hybrid power unit functions differently from the CSP-bio hybrid unit to provide electricity for the wastewater treatment system (Fig. 2b). Biogas serves as the thermal energy source of the power unit and is only utilized when the electricity from the PV (after DC to AC conversion, parasitic, and system losses) is insufficient to cover the electricity demand of the system (Fig. 4).

In order to understand the performance of the solar–bio hybrid power unit to satisfy the energy demand of the wastewater treatment, two scenarios of electricity generation with and without short-term solar energy storage were analyzed and compared.

3.2.3.1. Electricity generation without short-term solar energy storage.

A solar collection system without solar energy storage means that both thermal heat from CSP and electricity from PV are directly used by the solar–bio hybrid units for energy generation when DNI and GHI are available.

For the CSP-bio hybrid power unit, the hourly energy required from biogas (Q_B) is calculated as the difference between the hourly thermal energy required to generate the needed electricity ($Q\{P_{e\_af}\}$) and the hourly thermal heat collected from solar radiation ($Q_N \cdot \eta_h$) (Eq. (11.a)). While, the biogas energy needed for the PV-bio hybrid unit is the thermal energy required by the turbine to generate the electricity that compensates the insufficient electricity from the PV ($Q\{P_{e\_af} - P_v\}$) (Eq. (11.b)).

$$Q_B = \frac{Q\{P_{e\_af}\} - (Q_N \cdot \eta_h)}{\eta_b} \quad (11.a)$$

$$Q_B = \frac{Q\{P_{e\_af} - P_v\}}{\eta_b} \quad (11.b)$$

The solar operation factor (SOF) is a critical parameter to determine whether the solar–bio hybrid unit is a feasible solution to power the integrated AD and AET process. The SOF is defined as the time when CSP or PV units can collect net useful energy (the energy from biogas and solar energy collected after thermal and electricity losses to fulfill the minimum requirements of the solar–bio hybrid unit).

Since the solar–bio hybrid units need to provide a minimum energy input of 275.62 kWt (Table 2) to power the combined AD and AET processes, A_{SCA} was used to calculate the biogas daily balance of the solar–bio hybrid units. A positive biogas daily balance (m^3_{biogas}/day, the biogas amount required to generate Q_B) means that extra biogas is produced and can be stored for use at night or on cloudy days. A negative balance indicates that the daily biogas production is insufficient to cover the electricity demand of the wastewater treatment. An iterative approach was then applied to calculate the annual biogas balance. The annual biogas balance was used to evaluate the performance of the solar–bio hybrid power units. Without short-term solar energy storage, the CSP-bio hybrid unit at Phoenix and the PV-bio hybrid units at Lansing and Phoenix have positive net annual biogas balances, while the CSP-bio hybrid unit at Lansing has a negative net annual biogas balance (Fig. 5). The result indicates that PV-bio hybrid power generation works for both Phoenix and Lansing, while CSP-bio hybrid power generation only works for Phoenix. The low DNI and short daylight time during winter in Lansing are the main reasons that the CSP-bio hybrid unit cannot accumulate sufficient solar radiation to generate the required amount of the energy. It was also determined from the simulation results that the A_{SCA} of the CSP-bio hybrid and PV-electricity-bio hybrid power units were 21498 m^2 and 6128 m^2, respectively, in Phoenix, and the A_{SCA} of the PV-electricity-bio hybrid unit was 12030 m^2 in Lansing (Table 4). The A_{SCA} values enable the solar–bio hybrid units to store 87304 m^3 biogas for the CSP-bio-hybrid unit in Phoenix, 36175 m$^3_{biogas}$ for the PV-bio-hybrid unit in Phoenix, and 68507 m$^3_{biogas}$ for the PV-bio-hybrid unit in Lansing (Table 4), which are all larger than the corresponding biogas demands. Thus, self-sustaining wastewater treatment can be realized by PV-bio hybrid and CSP-bio hybrid power generation in Phoenix, and PV-bio hybrid power generation in Lansing.

However, since there is no short-term solar storage for the solar–bio hybrid power units, a very large area of solar collection is needed to generate energy during the daylight time to save the biogas energy for use at night or when cloudy. The large collection area leads to the generation of excess electricity and thermal energy from solar collection when DNI and GHI are at their maximum values (Fig. S3).

3.2.3.2. Electricity generation with short-term solar energy storage. Considering the large energy surplus from the solar–bio hybrid units without short-term solar energy storage, it is not a technically sound solution to use the solar–bio hybrid units to power the wastewater treatment. The short-term solar energy storage needs to be investigated to determine the optimal conditions of solar–bio hybrid power generation, so that Q_B and SCA both can be significantly reduced. A thermal reservoir for the CSP-bio hybrid unit and a battery bank for the PV-bio hybrid unit are used to store the extra solar energy when the DNI and GHI are higher than the requirements to fulfill the electricity demand of the wastewater treatment. The stored energy in the short-term storage is then used during the times when the DNI and GHI are not available to power the system.

Thermal collection for CSP uses a massive storage tank and saves the extra energy for electricity generation in the form of sensible heat, and the thermal storage is one-day sensible heat storage. The capacity of the battery storage for the PV is selected as half of the maximum daily electricity collection in a year. Eq. (11) can be modified to include the energy from thermal or electrical storage for the biogas balance.

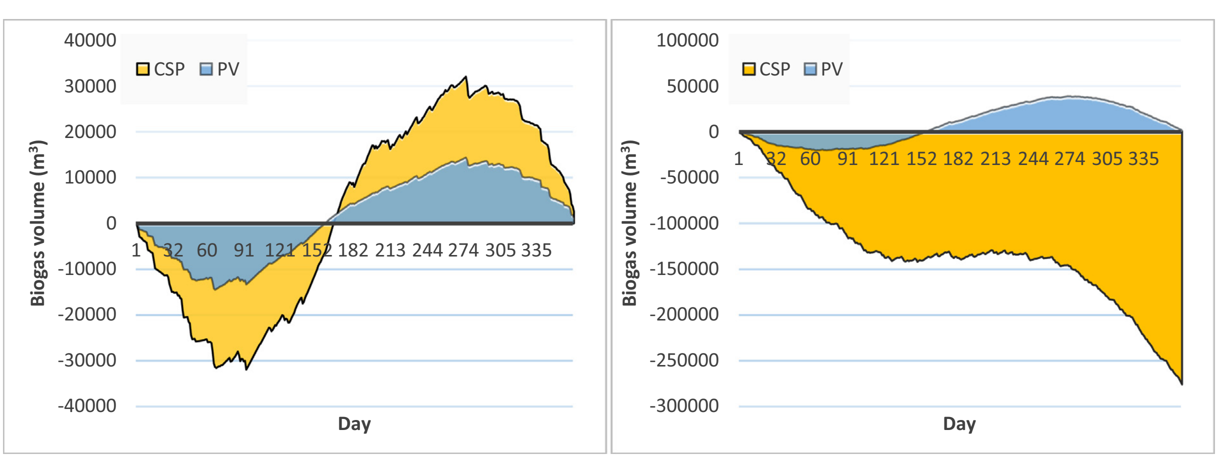
$$Q_B = \frac{Q\{P_{e\_af}\} - (Q_N \cdot \eta_h + Q_{s\_th})}{\eta_b} \tag{12.a}$$

$$Q_B = \frac{Q\{P_{e\_af} - P_v - P_{v\_b}\}}{\eta_b} \tag{12.b}$$

where Q_{s_th} is the thermal energy stored; and P_{v_b} is the electrical energy stored. The size for the energy storage is selected based on the thermal and electrical energy over-generated in the CSP and PV installation. The thermal storage for CSP at Phoenix and Lansing are 8851 kWht (thermal) and 26722 kWht, respectively. The battery bank size for PV in Phoenix and Lansing are 425 kWhe (electrical) and 1236 kWhe, respectively.

The iterative process calculated the A_{SCA} based on zero biogas balance in a year. The required A_{SCA} for CSP- and PV-collection are 3054 m^2 and 4032 m^2, respectively, in Phoenix. The required A_{SCA} for CSP- and PV-collection are 6756 m^2 and 5821 m^2, respectively, in Lansing. Fig. 6 shows the biogas accumulation for the selected solar collection area in a year. The annual biogas balance analysis indicates that, to maintain a net positive energy balance, the additional biogas for the CSP-bio hybrid and PV-bio hybrid power units are 135217 m^3 and 45054 m^3, respectively, in Phoenix; and they are 292486 m^3 and 113386 m^3 for the CSP-bio hybrid and PV-bio hybrid power units, respectively, in Lansing. The calculated A_{SCA} allows the CSP-bio hybrid and PV bio-hybrid units to store 137684 m^3 and 46002 m^3 biogas, respectively, in Phoenix; and 298098 m^3 and 117301 m^3 biogas, respectively, in Lansing. Since the solar–bio hybrid power units with short-term storage generate slightly more biogas energy than the demand of the wastewater treatment, the CSP-bio hybrid and PV-bio hybrid units both are capable of handling the weather variation and support the wastewater treatment in Phoenix and Lansing (Table 5).

In addition, the monthly surplus electricity of the solar–bio hybrid units with short-term solar storage is much lower than that of the units without short-term solar storage (Fig. S3). The corresponding A_{SCA} values were correspondingly smaller, which makes



(a) (b)

Fig. 5. Biogas balance without short-term solar energy storage. (a) Phoenix; (b) Lansing (Biogas balance at Lansing using an area of 500000 m^2 (CSP)).

Table 4
Biogas balance for the electricity generation (without short-term solar energy storage).

Location	Solar collection system	Solar collection Area (m^2)	Biogas deficit (m^3/yr)[A]	Biogas stored (m^3/yr)[B]	Biogas stored initial volume (m^3)	Biogas reserved (m^3)	Biogas tank capacity (m^3)[C]
Phoenix	CSP	21498	84647	87304	31905	2656	76.75
	PV	6128.6	35175	36275	14454	1100	34.61
Lansing	PV	12030.5	67098	68507	20073	1408	68.88

[A] Biogas deficit is the total biogas daily requirement that exceeds the daily generation of the AD.
[B] Biogas stored is the non-used biogas from the daily generation in the AD.
[C] Tank capacity considering a biogas compression factor of 500.

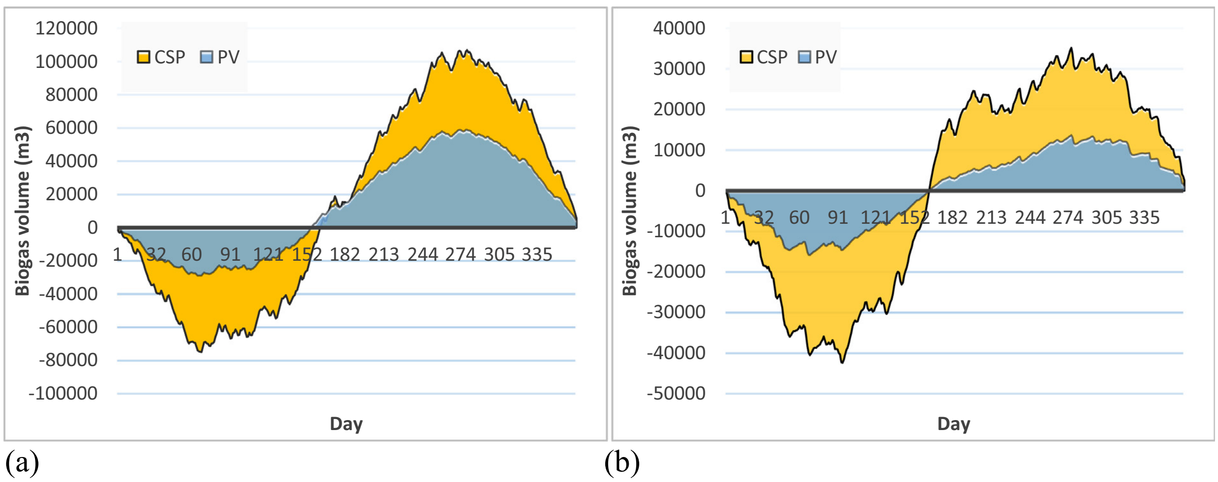


Fig. 6. Biogas balance with short-term solar energy storage. (a) Phoenix, (b) Lansing.

the solar–bio hybrid units feasible to be implemented at wastewater treatment facilities (Tables 4 and 5).

4. Discussion

This study presents a self-sustaining high-strength wastewater treatment concept for agricultural applications. Solar and biogas energy are used to support the treatment process including AD and AET. Based on geographic location of the treatment system, the effects of ambient temperature, DNI, and GHI on the system configuration and performance have been comprehensively investigated.

The AD unit in the self-sustaining system plays a dual role of reducing the organic matter and producing the biogas for electricity generation. The total solids in the AD influent (8.5%) were reduced by 41%, producing an average of 2919.9 m^3_{biogas}/day (0.48 m^3_{biogas}/kg $_{volatile\ solids}$ day) (Table 3 and Fig. 3). The biogas from the AD is a key energy component to realize the self-sustaining system (the energy of 7043.5 kWhe is required by the wastewater treatment, biogas can supply 5548.13 kWhe).

AD is a good energy generation unit, though it has limited capability to remove other nutrients, such as P and N, and reclaim the water. AET is then needed to post-treat the AD effluent and complete the wastewater treatment. AET requires a considerable amount of electricity (3832.8 kWhe per day, which is 54.4% of the total electrical consumption) to support the growth of aerobic microbes, leading to a negative energy balance for the wastewater treatment if the biogas is the only energy source for the combined AD and AET processes. Thus, a second energy source, solar energy, needs to be integrated into the system to satisfy energy demand of the AET. CSP and PV were the two selected solar energy collection methods for the solar–bio hybrid power units. The CSP-bio hybrid unit has the advantages of collecting energy at medium temperatures (<350 °C) and increasing the solar energy utilization efficiency ($\eta_{op} \cdot \eta_e$). The PV-bio hybrid unit has the advantages of generating electricity from diffuse solar radiation and having a higher SOF.

Energy balance analysis indicates that there is a significant difference in the solar collection area between solar–bio hybrid systems with and without short-term solar energy storage. Without

Table 5
Biogas balance for the electricity generation (with short-term solar energy storage).

Location	Solar collection system	Solar collection Area (m^2)	Biogas deficit (m^3/yr)[A]	Biogas stored (m^3/yr)[B]	Biogas stored initial volume (m^3)	Biogas reserved (m^3)	Biogas tank capacity (m^3)[C]
Phoenix	CSP	3054	135217	137684	42380	2466	93.05
	PV	4032	45054	46002	15848	475	35.43
Lansing	CSP	6756	292486	298098	74920	5612	218.13
	PV	5821	113386	117301	28864	3916	105.33

[A] Biogas deficit is the total biogas daily requirement that exceeds the daily productivity in the AD.
[B] Biogas stored is the biogas non-used from the daily generation in the AD.
[C] Tank capacity considering a biogas compression factor of 500.

the storage, the SOF must be maximized by increasing A_{SCA} to collect solar energy to obtain sufficient thermal energy for the CSP-bio hybrid unit, or sufficient DC current for the PV-bio hybrid unit to satisfy the energy demand of the wastewater treatment. With the storage, the SOF is significantly reduced for both CSP-bio hybrid and PV-bio hybrid units. Correspondingly, the values of A_{SCA} are also greatly decreased (Tables 4 and 5). In addition, the PV-bio hybrid unit has a lower A_{SCA} and smaller biogas storage tank than the CSP-bio hybrid unit at both locations of Phoenix and Lansing. It is apparent that the PV-bio hybrid unit is the preferred power solution for the studied self-sustaining high-strength wastewater treatment.

5. Conclusions

The solar–bio-hybrid power generation addresses the challenge of high-energy demand of the AET in the integrated system. The energy balance analysis demonstrates that biogas storage to store the extra energy generated by the solar–bio hybrid units during the warm months enables the wastewater treatment operation to be completely self-sustainable year-round. The PV-bio-hybrid unit with short-term energy storage requires a smaller solar collection area and smaller biogas storage tank than the CSP-bio-hybrid unit at both studied locations. Therefore, synergistically integrating PV-bio hybrid power generation, AD, and AET provides a technically feasible solution of a self-sustaining wastewater treatment.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2017.03.065.

References

Alvarez, R.E.A., Roman, M.B., Kirk, D., Chavarria, J.A.M., Baudrit, D., Pereira, J.F.A., Montero, W.R., Reinhold, D., Liao, W., 2016. Technical and economic feasibility of a solar-bio-powered waste utilization and treatment system in Central America. J. Environ. Manage. 184, 371–379.
APHA, 1998. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, D.C..
Axaopoulos, P., Panagakis, P., Tsavdaris, A., Georgakakis, D., 2001. Simulation and experimental performance of a solar-heated anaerobic digester. Sol. Energy 70 (2).
Chan, Y.J., Chong, M.F., Law, C.L., Hassell, D.G., 2009. A review on anaerobic-aerobic treatment of industrial and municipal wastewater. Chem. Eng. J. 155 (1–2), 1–18.
Cleaver-Brooks, 2011. The Boiler Book. Cleaver-Brooks, Milwaukee, WI.
Colmenar-Santos, A., Bonilla-Gomez, J.L., Borge-Diez, D., Castro-Gil, M., 2015. Hybridization of concentrated solar power plants with biogas production systems as an alternative to premiums: the case of Spain. Renew. Sustain. Energy Rev. 47, 186–197.
Deshpande, A.M., Satyanarayan, S., Ramakant, 2012. Kinetic analysis of an anaerobic fixed-film fixed bed-reactor treating wastewater arising from production of a chemically synthesized pharmaceutical. Environ. Technol. 33 (11), 1261.
EPA, 2000. Decentralized Systems Technology Fact Sheet. United States Environmental Protection Agency, Office of Water, Washington, D.C..
Federation, W.E., 2009. Design of Municipal Wastewater Treatment Plants MOP 8,. McGraw-Hill Professional.
Ge, H., Batstone, D.J., Keller, J., 2013. Operating aerobic wastewater treatment at very short sludge ages enables treatment and energy recovery through anaerobic sludge digestion. Water Res. 47 (17), 6546–6557.
HACH, 2004. DR/2400 Spectrophotometer Procedure Manual. HACH Company.
Hills, D.J., Stephens, J.R., 1980. Solar-energy heating of dairy-manure anaerobic digesters. Agric. Wastes 2 (2), 103–118.
Lazarova, V., Bahri, A., 2005. Water Reuse for Irrigation: Agriculture, Landscapes, and Turf Grass. CRC Press, Boca Raton.
Malcolm, J., Cassel, D., 1978. Use of Solar Energy to Heat Anaerobic Digesters. U.S. Environmental Protection Agency.
Martin, I., Pidou, M., Soares, A., Judd, S., Jefferson, B., 2011. Modelling the energy demands of aerobic and anaerobic membrane bioreactors for wastewater treatment. Environ. Technol. 32 (9), 921–932.
Mills, D., 2004. Advances in solar thermal electricity technology. Sol. Energy 76 (1–3), 19–31.
Mutamim, N.S.A., Noor, Z.Z., Abu Hassan, M.A., Olsson, G., 2012. Application of membrane bioreactor technology in treating high strength industrial wastewater: a performance review. Desalination 305, 1–11.
Novak, J.T., Banjade, S., Murthy, S.N., 2011. Combined anaerobic and aerobic digestion for increased solids reduction and nitrogen removal. Water Res. 45 (2), 618–624.
NREL, 2016a. Dynamic Maps, GIS Data, and Analysis Tools, vol. 2017.
NREL, 2015. National Solar Radiation Data Base. National Renewable Energy Laboratory.
NREL, 2016b. System Advisor Model. 2016.3.14 64 bit ed. National Renewable Laboratory, pp. SSC Version 159.
Ryckebosch, E., Drouillon, M., Vervaeren, H., 2011. Techniques for transformation of biogas to biomethane. Biomass Bioenergy 35 (5), 1633–1645.
Siva Reddy, V., Kaushik, S.C., Ranjan, K.R., Tyagi, S.K., 2013. State-of-the-art of solar thermal power plants—a review. Renew. Sustain. Energy Rev. 27, 258–273.
Speece, R., 1996. Anaerobic Biotechnology for Industrial Wastewaters. Archae Press.
Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., Yu, X., 2015. Selection of appropriate biogas upgrading technology – a review of biogas cleaning, upgrading and utilization. Renew. Sustain. Energy Rev. 51, 521–532.
UNEP, Corcoran, E., Arendal, G., 2010. Sick Water: The Central Role of Wastewater Management in Sustainable Development: A Rapid Response Assessment. United Nations Environment Programme, Arendal, Norway.
US-EPA, 2010. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008.
Wang, L.K., Pereira, N.C., Hung, Y.-T., 2009. Biological Treatment Processes, vol. 8. Humana Press, New York.
Ye, L., Zhang, T., 2013. Bacterial communities in different sections of a municipal wastewater treatment plant revealed by 16S rDNA 454 pyrosequencing. Appl. Microbiol. Biotechnol. 97 (6), 2681–2690.
Yue, Z.B., MacLellan, J., Liu, Y., Liao, W., 2013. Effects of corn stover as carbon supplement on an integrated anaerobic digestion and ethanol fermentation process. J. Renew. Sustain. Energy 5 (6).
Zhou, Z., Shen, X., Jiang, L.M., Wu, Z., Wang, Z., Ren, W., Hu, D., 2015. Modeling of multimode anaerobic/anoxic/aerobic wastewater treatment process at low temperature for process optimization. Chem. Eng. J. 281, 644–650.