Renewable Energy 83 (2015) 280–293

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Integrating solar energy into an urban small-scale anaerobic digester for improved performance

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ARTICLE INFO

Article history:
Received 27 January 2014
Accepted 28 March 2015
Available online

Keywords:
Anaerobic digestion
Biogas
Heat pump
Urban
Energy production

ABSTRACT

In this research, the feasibility of using an air-source heat pump as the main heating source for a 30 m^3 mesophilic digester located on the roof of an urban building was investigated during the coldest month of the year. A heat loss model for an insulated digester tank and adjacent rooftop greenhouse were developed as well as a heat transfer model for an air source heatpump. A 3-D model of the rooftop and surrounding buildings was developed in order to determine the effect of shadowing on solar energy gains of the greenhouse. Simulations of tank temperature fluctuation and resulting theoretical biogas production were performed for cases in which the heat pump was active only during daylight hours for each day of the month, every other day of the month, and for one third of the month including a full week without any heating. Results of the simulations show a daily temperature fluctuation of 0.2 °C for the first case, a fluctuation of 0.5 °C for the second case, and a maximum of 2.1 °C for the third case.

1. Introduction

As urban populations continue to grow to an estimated 70% of 9 billion by 2050, waste production and energy demands will rise as well [1]. As landfills surrounding increasingly populated cities fill to capacity and the price of transporting municipal solid waste (MSW) further away from city centers increases, the implementation of small-scale and municipal-scale anaerobic digestion systems to process the organic fraction of MSW (OFMSW) will undoubtedly become more prevalent. In the United States, OFMSW sent to landfills accounts for the third largest source anthropogenic methane emissions at around 100 million metric tonnes of CO_2 equivalent annually [2]. Although increased efforts are being made by the U.S. Environmental Protection Agency to capture this landfill gas for energy production, only an estimated 5–10% of landfills employ gas capture technology [3,4]. In 2014, the US Department of Energy released a comprehensive climate change action plan to reduce methane emissions by targeting biogas production from organic waste with the overall goal of reducing greenhouse gas emissions by 25% by 2020 [5]. The study states that in the U.S. there are currently over 2000 biogas facilities in operation with the potential for over 11,000 further systems to be implemented by 2030. As a waste-to-energy technology, anaerobic digestion represents an opportunity to greatly reduce greenhouse gas emissions while also providing a carbon-neutral source of heat and electricity.

The anaerobic digestion of OFMSW is feasible at smaller scales than currently being employed on farms and wastewater treatment facilities and can also be adapted to different urban environments. As fossil fuel prices continue to rise, implementation concerns with regards to the energy demand for maintenance of near constant temperatures (35 °C for mesophilic and 55 °C for thermophilic systems) need to be weighed against the energy content of the produced biogas [6–8]. At smaller scales and in colder climates, a larger percentage of the biogas produced is needed to heat the digester. If solar energy is used as the primary energy source for maintaining digestion process temperatures, the high methane content (60–70%) biogas produced from OFMSW could be made available for higher value energy applications (building heating, biofuels) [9].

In this paper, the feasibility of using an air source heat pump (ASHP) to transfer the solar heat gains of a greenhouse to a 30 m^3 mesophilic digester located adjacent on the roof of an urban building in the downtown area of Montreal, Canada, is investigated during the coldest month of the year. A heat loss model for an insulated tank and a heat pump heat transfer model have been developed. Hourly ambient temperatures, dew point temperatures, and wind speed data from National Resources Canada were used for

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http://dx.doi.org/10.1016/j.renene.2015.03.073
0960-1481/

the month of January 2012. In order to calculate the solar energy available during this time to heat the digester, a 3-D model of the proposed building and the neighboring buildings has been constructed. The model is analyzed for hourly solar radiation with the shadowing effect of surrounding buildings considered to increase the accuracy of calculations.

2. Materials and methods

2.1. Description of the proposed system

The anaerobic digester tank is to be located outdoors, adjacent to an existing greenhouse with a volume of 1725 m^3 and 627 m^2 of surface area on the roof of a 13-story building at a height of 43 m oriented south by southwest. Instead of being vented to the atmosphere, the low-grade heat that builds up in the apex of the greenhouse during the day will be ducted to an air source heat pump, upgraded, and used as the main heating source for the digester. In order to ensure stable and optimum biogas production, the OFMSW slurry in the tank requires minimal daily temperature fluctuations as the bacteria are sensitive to temperature shock.

The tank proposed is a 30,000 L polyethylene rainwater storage tank with a diameter of 4.3 m, a height of 2.6 m, and wall thickness of 0.025 m. Polyurethane spray foam is considered for tank insulation as it will provide a uniform covering without seams and will therefore have lower heat losses than using Rockwool insulation plus aluminum or steel cladding. Insulation for the tank bottom is selected to be 0.076 m foam glass insulation. The bottom of the tank is resting on 0.2 m of concrete with an indoor temperature of 20 °C maintained below. A diagram of the proposed ASHP system and urban rooftop location can be seen in Fig. 1.

For this system a mesophilic temperature range (35 °C) with a 30 day retention time has been chosen as opposed to a thermophilic system (55 °C) due to the fact that when dealing with a small-scale system in a cold climate, the heating requirements as well as insulation requirements will be considerably lower. It is plausible that any surplus yield in energy production from a slightly higher biogas output available from thermophilic digestion would be less than the increase in energy demand required to increase process temperature by 20 °C or 35%. Although thermophilic digestion allows for smaller digester size (a possible benefit for urban implementation) there are other issues to consider as well. Thermophilic digestion allows for shorter retention times for similar methane production as mesophilic digestion, but it has been shown that the treatment of substrates with high biodegradability as well as variability, like food waste, can lead to increased acidity as the volatile fatty acids produced build up faster than the methanogens can convert them, leading to a generally more unstable system [8,10].

The system being investigated includes a smaller hydrolysis tank located indoors with a grinder attached to the top that the food waste (diluted with warm water) is loaded into on a daily basis. Fresh substrate is added to the main digester tank outdoors through a three way valve that leads to a circulation loop with heat-jacketed piping that provides heating and additional stirring of the tank slurry. There should be little if any heat shock to the system from loading fresh food waste.

The normal stable temperature range for mesophilic digestion occurs around 35 °C ± 3 °C [8]. In the *Municipal Wastewater Treatment Manual of Practice* it states that the daily temperature variation for an anaerobic digestion system should not exceed 0.6–1.2 °C [11]. These temperature ranges will be taken into consideration when determining the feasibility of simulated tank temperature fluctuation when heating with the air source heat pump.

The system is investigated during the month of January, the coldest month of the year, which has an average of 8 h of usable solar radiation. Once the sun sets in the evening, the digester tank will receive no heating for approximately 16 h until the next sunrise. A heat loss model of the system was developed in order to verify insulation requirements and ensure the feasibility of stable biogas production under these cold-climate operating conditions.

2.2. Digester tank heat loss modeling

A basic electrical equivalent model of the thermal model of the system is shown in Fig. 2. Due to the fact that the tank will be stirred for fewer than 8 h per day, it is assumed that the slurry is stationary and there is no internal convection between the slurry and the tank walls or the slurry and the gasses located above. It is also assumed that the gas is the same temperature as the slurry. In Fig. 2, conductive heat losses propagate from the thermal capacitance (*Thermcap*) through the walls, roof, and floor of the tank and then continue through the insulation and are referenced as $R_{condtank}$ and $R_{condinsul}$ for each of the branches in the diagram. In the case of the floor, the heat losses continue through the insulation to the concrete below in an effort to equalize with the indoor temperature maintained at 20 °C ($T_{indoors}$). From the outer shell of the wall and roof insulation, forced convection losses occur in parallel with radiation losses to the sky and are labeled as $R_{convinsulair}$ for the walls and roof branches. Due to the fact that the actual ambient temperatures, sky temperatures, and the wind speed values required for an accurate simulation are neither constant nor sinusoidal, a more flexible and dynamic model is required.

A model of the system that includes input tables for measured hourly weather data (temperature, wind speed) was developed using Wolfram's *System Modeler*. An air source heat pump model was developed and connected to the thermal capacitance of the tank as a heat source. Additionally, the model could be expanded to allow for multiple types of heating inputs in parallel. The *System Modeler* schematic overview can be seen in Fig. 3 with nested models for the heat pump, T_{sky} calculation, and wind speed coefficients for the convection modules.

The components of Fig. 3 include a heat capacity module, three parallel branches of conduction modules for the headspace, polyethylene tank, insulation, floor, walls, and roof, two forced convection modules for the walls and roof in series with the conduction modules with inputs for height-corrected wind speed data, two radiation modules for the tank walls and roof in parallel with the convection modules that are connected to the sky temperature which is derived from hourly dew point and ambient temperature data. A constant internal building temperature was set at 20 °C.

The thermal conduction properties and surface areas of the tank and insulation are shown in Table 1. The System Modeler heat transfer conduction modules require only the thermal conductance in (W/K) to be input for each conduction component. For the convection modules, the convective thermal conductance (G_c) is required and the following equation (defined in the module) for forced air convection (v > 5 m/s) is needed as an input parameter [23]:

$$G_c = Area*7.2*(windspeed\ in\ m/s)^{0.78}\ in\ W\Big/\left(m^2*K\right) \qquad (1)$$

The wind speed data was obtained by adapting NRCAN measurements taken at 10 m and correcting for building height by using the power law described in Eqn. (2) [12]:

$$v_W(h) = v_{10}*\left(\frac{h}{10}\right)^a \qquad (2)$$

Where: