Development of a Combined Solar Bioenergy Plant for Disposal of Household Waste

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Research Article

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Abstract

This article presents one of the methods for modernizing a biowaste plant. Development opportunities are also being discussed to optimize the installation to maximize energy and environmental benefits. Methods for the biogas production, electrical energy and biological residue were considered and an analysis of the mass balance of the plant inputs and outputs was carried out. The energy and its environmental impact of the facility was assessed and ascertained that the facility has noteworthy ecological benefits. However, the research work elaborated by analyzing the plant operational material balance, that the quantity of methane generation and therefore the electricity generated can be further enhanced by combining this plant.

1. Introduction

The cost and safety of energy, greenhouse gas emissions and additional pollutants from prevailing energy generating facilities are two major issues that have directed to numerous technological advancements in the field of renewable energy sources. In the global arena, the biomass-based energy generation is a green and clean source of energy. Additional issue is on the effective management of municipal solid waste (MSW), since the organic portion of MSW paves the way for boundless methane emissions when buried without treatment. However, the hasty urbanization of landfills, there are fewer and fewer and strict laws in place, in particular limiting the disposal of degradable waste in landfills.

The country has approved a strategy for the management of municipal solid waste Uzbekistan for 2019–2028 (CIS Legislation of Russia 2019).

It is assumed that its implementation will create an effective system for processing solid domestic waste with the necessary infrastructure, improve pricing and optimize tariffs in the field of sanitary cleaning, reduce the volume of waste sent for landfill disposal, and use waste as an alternative fuel.

2. Main Part

Anaerobic digestion is adopted for processing the organic solid waste to generate biogas as an alternative to LPG (Liquefied petroleum gas) and natural gas. The slurry is an organic left-over material of anaerobic digestion, supplied to the agricultural land (without any maturation) as biofertilizer for replacing chemical fertilizers. In addition, slurry holds enriched nutrients like nitrogen and phosphorus in its composition. Thus, anaerobic digestion from biowaste combines energy generation with environmental benefits.

The design consideration for the reactor and the characteristics of the anaerobic digestion process have attracted the attention of several investigators. (Igoni, A. H., C. L. Eze 2005) investigated the design of municipal solid waste-based biogas plant for biogas generation and analyzed the performance by correlating the effects of several constraints such as pH, C/N ratio, moisture content, waste particles

 C. J. Banks 2012) associated the fermentation effectiveness of the original categorized municipal waste and the automatically categized portion of the solid waste. They summarized that a significant energy potential can be achieved by increasing the percentage of biodegradable portion (organic material) by separating organic material at the source level.

The solid organic waste undergoes a putrefaction process which, generate some mixture of gases; predominately methane (CH_4), carbon dioxide (CO_2) with oxygen (O_2) and N_2. The significant heating value of CH_4 in biogas can make biogas as an excellent source of sustainable and eco-friendly energy resource. The calorific value of biogas is proportionate to the concentration of methane (CH_4) content in the biogas. However, the quality and quantity of biogas produced in landfills mainly depends on the characteristics and density of municipal solid waste in landfills. The configuration of organic and inorganic waste and the density of the landfills will alter the CH_4 concentration. Study by (Mohamad Y.Mustafa, Rajnish K. Calay 2016) focused on measurement of CH4 content in solid waste of various densities, as well as determining the composition of solid waste. The result shows that the methane (CH_4) content ranges from 3–57.7%, from 2.19–42.24% CO_2 and approximately 1.21–7.92% O_2. The occurrence of inorganic waste and the level of density of the waste affects the putrefaction frequency and methane (CH_4) composition.

In another research work, (Banks, C., M. Chesshire 2011) observed an anaerobic digester with a biological cycle in South Shropshire, UK, for 14 months and again found that the waste, separated by source, is easily biodegradable and produces biogas with 60% methane. The energy balance of 400-kWh is achieved from each ton of recycled waste processing. These studies recommended the predicted biogas generation from the municipal solid waste management.

Installation specifications

This research work examines the features and principle of operation of a combined bioenergy plant. Safe disposal of waste with the implementation of the proposed innovative installation is a useful and optimal method. The principle of operation of the pyramid-shaped installation is based on the thermal conductivity of materials.

The 10 to 15 tons of organic household waste is the total capacity of the plant. Also, it has an electric power of 7.8 kW from installed solar panels.

Raw materials and energy balance

The organic portion of the residential and commercial municipal solid waste are the key biomass sources considered.

According to experts in the republic, the amount of waste from industrial and household spheres is 100 million tons. And the share of household waste is 9 million tons, and only 9% is recycled. Each million tons contains 360 thousand tons of food products, 160 thousand tons of paper and cardboard, about 55 thousand tons of textiles, about 45 thousand tons of waste from plastic and other components.

Currently, on the example of the Fergana region, an average of 3.5 tons of waste is generated per day, 105 thousand tons per month and 3 million 260 thousand tons of household waste per year. If we consider an example only for Fergana, then if all the garbage thrown out in a year is distributed in an even layer over the city, the thickness of this layer would be about 7 centimeters (Murodov M.H. 2019) .

Mixed food and organic waste: $C_6H_{9.6}O_{3.5}N_{0.28}S_{0.2}$

Mixed paper (waste paper): $C_6H_{9.6}O_{3.54}N_{0.036}S_{0.01}$

The minor components like sulfur and nitrogen are found significantly in the mixed and organic food waste. Furthermore, excluding the nitrogen and sulfur, the waste paper molecular structure has a very close structure of cellulose, $(C_6H_{10}O_5)_x$. In addition, if we do not take into account minor elements, the average molecular structure of organic compounds in solid waste can be approximated by the molecular composition $C_6H_{10}O_4$ (Themelis 2002).

Biogas is a biodegradable waste component from nuclear power plants and contains mainly methane (CH4) and carbon dioxide (CO2). The traces of non-methane organic mixtures is noted in the gas concentration, which comprises of air impurities and volatile organic mixtures.

The anaerobic digestion (or) bio methanation (or) methane fermentation carried out by the following four stages:

1. Hydrolysis or fermentation: The breakdown of complex organic particles (cellulose, proteins and fats) into simple sugars, amino acids and fatty acids by hydrolase, an exoenzyme. Hydrolysis of carbohydrates occurs within a few hours, while proteins and lipids are degraded after a few days.
2. Acidogenesis or formation of organic acids: The acidogenic microorganisms is employed for absorbing the monomers produced in the hydrolytic phase. Therefore, the further decomposition into short-chain organic acids, alcohols, hydrogen and carbon dioxide is ensured.
3. Acetogenesis. The acetogenic microorganisms break down hydrogen and carbon dioxide to form acetic acid and acetate. Acetate assists as a substrate for methane-producing microorganisms and acetogenic microorganisms, which grow synergistically with methane-producing bacteria.
4. Methanogenesis. In the last stage, microorganisms known as methanogen convert acetic acid to methane, CO_2, and water. During this phase, rotten mass is formed, which is nutrient-rich by-product. The pH range of 5.5 and 8.5 is suitable for better gas generation and 30 and 60°C temperature range is preferred for enhancing the fermentation frequency (Naik, N., E. Tkachenko 2013).

As elucidated in the process of anaerobic digestion (after fermentation and the formation of organic acids), methane is generated by methanogenic microorganisms, either by decomposing acids to methane and carbon dioxide, or by controlling the carbon dioxide with hydrogen. Two characteristic reactions are given in the following equations:

Acetogenesis

$$C_6H_{12}O_6 \underset{\Rightarrow}{yields} 2C_2H_5OH + 2CO_2$$

1

Methanogenesis

$$CH_3COOH \underset{\Rightarrow}{yields} CH_4 + CO$$

2

$$C_6O_2 + 4H_2 \underset{\Rightarrow}{yields} CH_4 + 2H_2O$$

3

During the anaerobic decomposition, the quantity of natural gas formation is determined by an basic molecular formula (Themelis 2007) :

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2$$

4

From Eq. (4), neglecting the additional minor components such as moisture and inorganic elements, the molar ratios of CO_2 and CH_4 in the product are 54% and 46%, respectively. Though, (Angelidaki, I., D. Karakashev 2011) proposed another formula, in which the molar amounts of CO_2 and CH_4 in the product are identical; this is revealed in Eq. (5):

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \underset{\Rightarrow}{yields} \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CO_2$$

5

Ratio between CO_2 and CH_4 be subject to the oxidation state of the carbon existing in the organic material. The reduction of organic carbon leads to increase in the methane (CH_4) generation (Angelidaki, I., D. Karakashev 2011) .

By assuming the following, the waste material comprises 70% of biomass, and dry organics amount to 60% of the biomass. Thus, the total mass of dry organic material ($C_6H_{10}O_4$), is corresponding to 420 kg/tonne of waste material.

The molar mass of ($C_6H_{10}O_4$), is 146 g/mole, which means that 420 kg of the material is equivalent to 2.56 kmol.

By using the equations 4 and 5, a yield of 3.25 moles of CH_4 for each mole of ($C_6H_{10}O_4$) is obtained. In addition, the expected yield of methane is 8.32 kmol per tonne of waste material. By considering the mass, 133,5 kg or 0.1335 tonne of methane per tonne of solid waste is estimated.

By considering 25 % as the thermal effectiveness for electricity production at the plant level, and considering the Lower Heating Value (LHV) of methane (which is 50,000 kJ/kg), the total electricity produced per tonne of waste material will be conferring to the Eq. (6) (Mohamad Y.Mustafa, Rajnish K. Calay 2016):

$$133{,}5[kg/tonne] \; 50000[kJ/kg] \; 0{,}25 = 1668750 kg/tonne$$

6

The above expressions help in calculating the yield and quantity of biogas generated from household waste. The factor influencing the success of the process – temperature, plays an important role in achieving maximum results in the calculations. Based on the above factors, it can be concluded that the efficiency of biogas conversion is highly dependent on the temperature inside the installation.

Methane bacteria manifest their vital activity within the temperature range of 0 ÷ 70 ºC. If this temperature is higher, the bacteria begin to die, with the exception of a few strains, which show their viability at ambient temperatures up to 90 ºC. At subzero temperatures, they only survive, but cease their vital activity.

The degree of bacteriological methane formation further increases with increasing temperature. But with an increase in temperature, the amount of free ammonia also increases, when a certain concentration of ammonia is reached, the fermentation process can not only slow down, but also practically stop. Another limiting factor for temperature rise is the cost of heat energy required to heat the substrate, since a one degree increase in temperature does not provide a directly proportional increase in gas production (Fig. 1). As for the lower temperature limits, biological plants without reactor heating can have a positive performance only at 51°C with an average annual outside temperature of about 20°C and higher, but not lower than 18°C. If the temperature of the biomass is less than 15°C, then the biogas yield is so low that the process of gas formation practically stops. Such a biological plant without heating and thermal insulation ceases to be economically profitable (V. Baader, E. Done 1982).

General gas outlet; methane outlet.

To ensure a stable and required substrate temperature inside the plant, we offer heating the biogas plant outside. This process is carried out using solar panels that are coated on the outside of the installation.

Solar panels are the most promising and widely used renewable energy technology on the global market today. While solar panels are simple to make and readily available, even the best solar panels convert only a fraction of the energy from the sun into electricity.

In practice, a large portion of the sun's energy is spent on heating and overheating the solar panel elements. Under normal operating conditions, solar cells, depending on the geographical latitude (longitude) in the summer season, can heat up to 90 degrees Celsius or even more.

Overheating degrades efficiency more noticeably and can shorten the life of the photocells. Ventilation, active cooling, coolants, and other means to reduce the surface temperature of a solar cell are expensive and sometimes cannot optimize the system (Tursunov M.N, YUldoshev I.A, Tukfatullin O.F, Sungjin Kim, Soon-Wook Jeong, Amir Abidov 2010).

Solar cells directly convert photon energy into electrical energy. When photons pass through the semiconductor areas of photovoltaic panels, they generate electrons from atoms, i.e. produce electric current or photo EMF. The most successful and widely used solar cell designs – silicon semiconductors – today convert less than 30% of the energy they receive, even at their peak of efficiency.

The rest of the solar energy, which is not converted and generates excess heat, when the solar cell is heated, reduces the performance of the battery (Kang, X., C. Wang, Y. Wang 2018). Each degree increased will reduce the efficiency of the photocell by about half a percent. This decline is quite significant: solar energy is investing heavily in solving the problems associated with solar cell heating.

The proposed new method changes the design of solar cells, mainly a biogas plant, in order to increase the efficiency of key cells.

A large proportion of the photon energy is spent on heating, overheating of the solar battery cells. Under normal operating conditions, photocells can heat up to 55 ° C and even more. As the surface overheats, the efficiency of the photocell deteriorates and the shelf life is reduced. Existing methods of cooling the surface of a photovoltaic cell pays off passively, while the consumed energy for cooling is provided by a photovoltaic battery (Hao et al. 2019).

In our case, thermal energy is transferred to the substrate through photovoltaic panels that are overheated when exposed to direct sunlight. Heat transfer on the front layer of solar panels is carried out using the thermal conduction method. The heat exchanger, which is located on the front layer, directly passes thermal energy through itself to the substrate. Due to the transferred thermal energy, the concentration of the resulting biogas increases.

In biogas plants equipped with mixers, simultaneous mixing and heating of the circulating and fresh substrate allows you to accurately control the fermentation temperature. At the same time, the high speed of movement of raw materials avoids the formation of solid deposits on the heating surface. If necessary, the heaters outside the reactor can be easily serviced or repaired.

The installation looks like a pyramid (Fig. 2). The height of the pyramid installation is h = 7.2 m, the length of the side edge is a = 10.2 m. In this case, up to n = 78 pieces of solar panels can be placed on one side of the pyramid, each of which generates electrical energy with a power of P_1 = 100 W. The total generated power of one side of the pyramid is P_{total} = 7800 W of electrical energy. The second side of the pyramid equipped with photovoltaic panels also has electrical parameters as the first.

3. Results And Discussions

By getting rid of unwanted heat radiation, the efficiency of the solar panel increases by 15–30%. Due to the received thermal energy from the heat exchanger, which is located on the front layer of the photovoltaic panel, the efficiency of biogas formation increases by 30–40%.

The two sides of the pyramid used are designed to add power and increase the efficiency of converting solar energy into electricity as the sun moves throughout the day.

4. Conclusion

Using our proposed innovative method for waste disposal, the following conclusions can be made:

- Formation of biogas and electrical energy;
- Provision of a stable temperature inside the unit by maintaining excess thermal energy on the surface of solar panels built in the outer area of the biogas plant;
- An alternative way of utilization of household waste and the method to improve efficiency and reduce energy losses in converters have been developed;
- A stable temperature will rise the methane yield and enhance the quality of the generated biogas, which, most likely, occurs in the process, but this requires additional research to determine the method of heat transfer to the substrate;
- The amount of biogas (methane) produced by the plant can be significantly increased in comparison with traditional plants in which the substrate is not heated;
- In fact, electricity is produced, which serves to provide electricity to energy consumers and the gas output from the installation is improved (maximum 40% of the theoretical potential);
- Cooling the surface of photovoltaic panels by transferring excess heat to the substrate increases the power generation potential by 25–30% and prolongs their life.

Declarations

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Ethical approval

This paper does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate

Not applicable.

Consent to publish

Authors transfer to Springer the publication rights and warrant that our contribution is original.

Authors’ contributions

All authors contributed to the study, conception and design. Material preparation, data collection and analysis were performed by Murodov Muzaffar Khabibullaevich. The first draft of the manuscript was written by Kanagavel Pitchai and all authors commented on the previous version of the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of Data and Material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

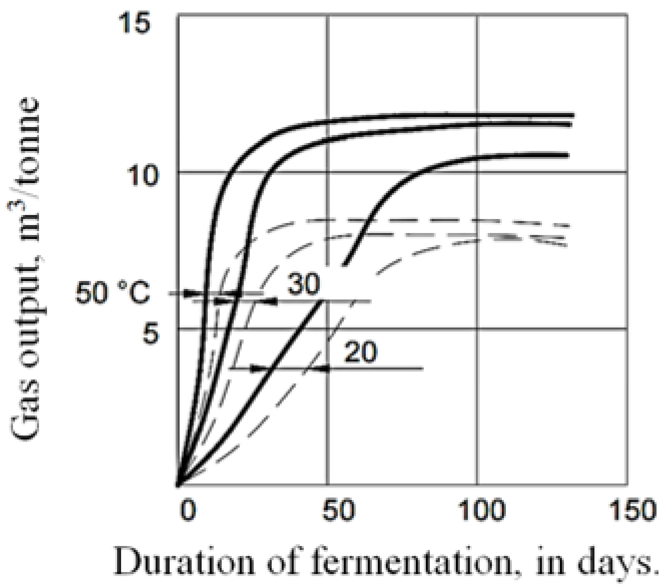

Figure 1

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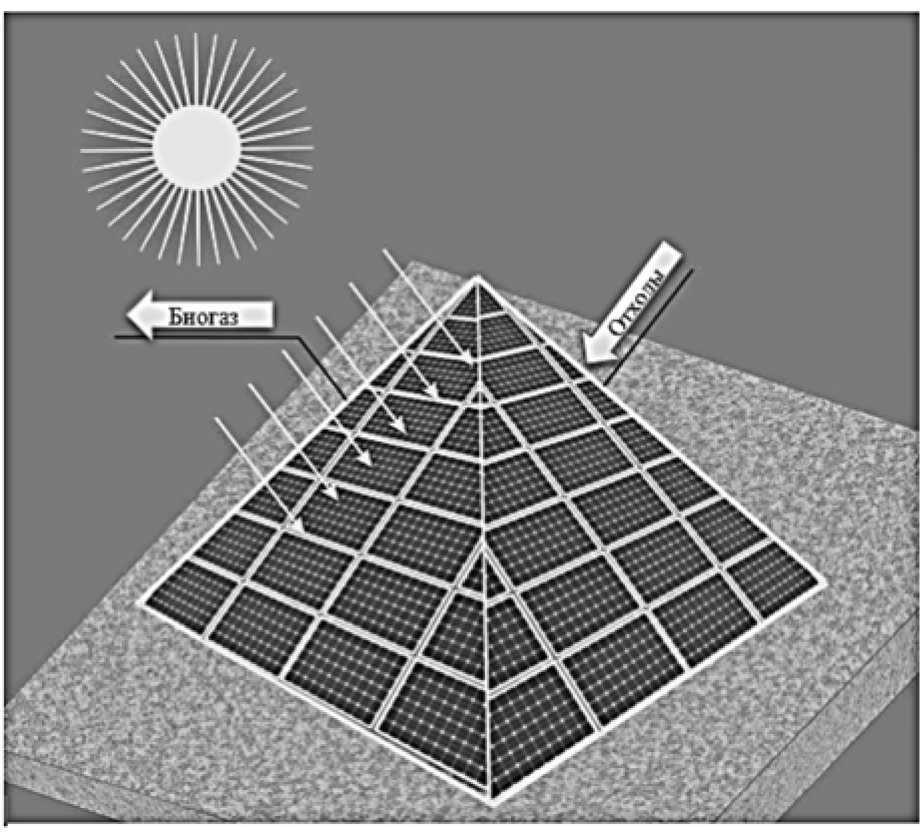

Figure 2

Exterior view of the pyramid-utilization unit

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