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Comparison of Different Methods (Digestion, Combustion, Gasification, and Pyrolysis) for Sludge Energy Recovery: A Case Study for Ekbatan's Municipal Treatment Plant

A. Hemmati [*]***, T. Abedzadegan***

Petroleum and Chemical Engineering Department, Science and Research Branch, Islamic Azad University, Tehran, Iran

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ABSTRACT

Different methods for urban sewage sludge energy recovery, such as burning, gasification, pyrolysis, and digestion, based on the net energy production efficiency, advantages and disadvantages, and complexity of these processes have been investigated in this article. The best method for energy production from sludge was selected among different methods according to energy and the amount of greenhouse gas production. The capacity of the constructed power plant was calculated and investigated economically for each scenario. Quantitative and qualitative information on sludge was required to carry out this research; thus, Ekbatan wastewater treatment sludge was analyzed. The results showed that the sludge of this treatment plant had 5.7 % solids, containing 65.7 % volatiles, and the dry heat value was about 15,100 kJ/kg. It was found that the best scenario for sludge energy production in this treatment plant is a digestion process with pure net energy production of 73.2 × 107 kJ/d. The energy recovery in an anaerobic digester can prevent the emission of 16,680 ts of CO_2 annually and release about 1,460 tons of CO_2 per year. The chemical analysis shows that the selected sludge has a potential production of $25m^3$ of CH_4 for each m^3 of sludge. The annual amount of biogas that can be recovered from municipal treatment plant is 836543 m^3. The heat value of this biogas is equal to 475,514 kJ/m^3. Therefore, with a typical treatment plant, an annual consumption of 475,514 m^3 of natural gas will be saved. On the other hand, the biogas can be used to generate electricity. The power of the plant is about 216.8 kW such that with the construction of this power plant, the annual saving of 1.5 million dollars will be realized.

1. Introduction

The release of sludge in the environment due to the presence of corrosive substances and pathogens leads to the spread of diseases and environmental degradation. Sludge management by wastewater treatment plants is a major waste management sector. On the other hand, the progressive consumption of

[*]Corresponding author: azadehhemmati@yahoo.com

energy in recent decades has led to an energy crisis in the world. Pollution caused by the combustion of fossil fuels causes environmental problems, and the expiration of these resources has led industries to seek the use of renewable energies. These two issues make consideration for sludge purification with the goal of energy recovery. In this paper, various methods of energy recovery from urban sewage sludge including burning, gasification, pyrolysis, and digestion have been investigated and compared based on energy recovery and economy.

2. Materials and methods

A complete quantitative and qualitative analysis of certain sludge was required for this research. Therefore, the sewage sludge of Ekbatan (located in the west part of Tehran) as an example of municipal sewage sludge was selected as a case study. The maximum discharge of this treatment plant is about 4,500 m^3/d for 100,000 people. The BOD is 200 mg/l for influent and 20 mg/l for effluent approximately. The system works based on the conventional activated sludge. The average discharge rate of the sludge is about 100 m^3/d.

In the next step, sludge samples were analyzed to determine the percentage of the moisture, solids, volatile solids content, elemental analysis of CHSNO, and thermal properties. The results of sludge analysis, quantitatively and qualitatively, consider the amount of the energy produced by each method, the amount of the greenhouse gas production, as well as the strengths of each process. By suggesting the most appropriate method, the amount of net energy produced and the amount of greenhouse gas produced by this method were calculated; for this amount of energy, the capacity of the constructed power plant was calculated and evaluated economically.

Primarily, the percentage of moisture content, percentage of solids, and percentage of solid evaporation were calculated according to the standard method. In the next step, to obtain the sludge chemical formula, it is necessary to determine the percentage of the main elements forming the sludge. To this end, the elemental analyzer (CHNSO), which consists of two techniques including rapid combustion and gas chromatography, was used for a sample of dry sludge at 105 °C. The calorimetric device was also used to determine the thermal value of the dry sludge dried at 105 °C [1].

In order to ensure the accuracy of the results, samples were taken and analyzed three times in two months, and its average was the basis of the calculations. The results of the experiments are summarized in Table 1.

Regarding the percentage of the elements, its proximate chemical formulation is estimated below:

$C_{34.8}H_{54.3}O_{14.3}N_{1.7}S_{0.38}$

The thermal value of wet sludge using the correlation was provided by Sokhansanj [2].

$$LHV=HHV(1-M)-2.447M = -1.86\ \frac{MJ}{kg} \qquad (1)$$

In the above correlation, LHV is the thermal value of the wet sludge, HHV is the thermal value of the dry sludge (HHV=15.31), and M is Mass fraction. Then, 2.447 is the amount of the energy needed to evaporate water at 25 °C.

3. Results and discussion

Various methods for energy production from sludge were investigated based on the sludge analysis. By calculating the net energy production, the energy recovery efficiency for the burning process was around 55 % and about 90 % for the pyrolysis process. It was equal to 80 % for the gasification process and 70 % approximately for the digestion process.

Table 1
Qualitative analysis of sludge results.

Parameter	First sample	Second sample	Third sample	Average
% Moisture	94.6	94	94.2	94.3
% Solids	5.4	6	5.8	5.7
% Volatile solids (TS %)	64	71	62	65.7
% Carbon	35.78	38.6	32.72	35.7
% Hydrogen	4.47	4.1	5.35	4.64
% Nitrogen	2.87	1.9	1.32	2.03
% Sulfur	0.54	0.8	1.78	1.04
% Oxygen	18.34	19.6	20.77	19.57
Thermal value of dry sludge (MJ/kg)	15.31	14.98	15.12	15.1

3.1. Energy efficiency of anaerobic digestion

The amount of the biogas and energy produced in rapid digestion at 35 °C and the sludge retention time of 20 ds[3,4] have been calculated using two methods of a chemical formula of dry matter and the sludge removal efficiency of volatile solids.

3.1.1. Biogas production potential using a chemical formula on dry basis

By using the sludge dry matter formula, the potential of biogas production was estimated using the stoichiometric equilibrium and the approximate equations. The following equation was used to calculate the production of biogas in a digester [5].

$$C_vH_wO_xN_yS_z + (v-\frac{w}{4}-\frac{x}{2}+\frac{3y}{4}+\frac{z}{2})\ H_2O \rightarrow (\frac{v}{2}+\frac{w}{8}-\frac{x}{4}-\frac{3y}{8}-\frac{z}{4})\ CH_4 + (\frac{v}{2}-\frac{w}{8}+\frac{x}{4}+\frac{3y}{8}+\frac{z}{4})\ CO_2 + z\ H_2S + y\ NH_3 \quad (2)$$

As a result, the biogas production was estimated using the chemical formula of the dry sludge, as shown below:

$$C_{34.8}H_{54.3}O_{14.3}N_{1.7}S_{0.38} + (13.67)\ H_2O \rightarrow (19.88)\ CH_4 + (14.92)\ CO_2 + (0.38)\ H_2S + (1.7)\ NH_3 \quad (3)$$

The high equilibrium shows that, for 34.8 moles of organic carbon, 34.8 moles of biogas are produced containing 19.88 moles of CH_4 and 14.29 moles of CO_2. The methane percentage in biogas is equal to 57.1.

$$\frac{19.88}{34.8}=57.1 \quad (4)$$

The results of the calculations show that each liter of sludge has the potential to produce 25 liters of methane.

According to 100 m^3/d slurry discharge, the biogas and methane production are 4378 and 2,500 m^3/d, respectively. As a result, the amount of energy production based on the methane thermal value (35,850 kJ / m^3) is about 8.96×10^7 kJ / d.

This amount is the maximum amount of the energy produced by the digestion method according to the properties of the sludge, assuming that the whole organic sector of the sludge is converted to a biogas without any production of the new and residual cells.

3.1.2. The biogas production by using volatile solids removal rates

The solid reduction occurs when sludge is heated up. This can show the stability of sludge based on the volatile solids. The reduction of volatile solids in high-density micelles is typically between 50 % to 65 % [6]. According to the following formula, the amount of volatile solid elimination is calculated as below [7]:

$$V_d = 13.7 \ln(SRT) + 18.9 = 60 \quad (5)$$

when V_d is the reduction of volatile solids (%), and SRT_d (20 ds) is the solids retention time.

Gas production in digesters is a direct result of the destruction of volatile solids. The total amount of gas production for sludge is between 0.8 to 1.2 m^3/kg volatile solids. The gas production will increase if the sludge has a high amount of grease and oil and the SRT is provided sufficiently. The average value is estimated around 1 m^3/kg. According to the amount of the volatile solids and the production of the biogas, the amount of energy production can be estimated [7].

As a result of the experiments, 65.7 % of the total solids in the sludge were volatile solids. However, the total volatile solids produced can be from 3819.8 to 2291.9 kg/d. The produced biogas is about 2291.9 m^3/d. According to the calculation of 57.1 % methane produced by the gas, the production rate of methane is estimated to be 1308.6 m^3/d. The amount of the energy produced from this volume of methane is supposed to be 4.69×10^7 kJ/d, which is the energy extracted from a high-rate anaerobic digester with 20 d retention time.

3.1.3. Energy consumption in the anaerobic digester

The energy required for the anaerobic digestion process involves the electrical energy used for sludge mixing, the heat needed to increase the temperature of the sludge to reach 35 °C, and the heat released from walls, the floor, and the ceiling of the digester.

The electrical energy required for mixing is determined by the mixing method. The power required for this system is around 5-8 W/m^3. For the mechanical mixing systems, the required power is 7 W/m^3 [3]. Due to the amount of sludge discharge, the total electrical energy consumption was estimated about 69,120 kJ/d.

The heat value needed to increase the temperature of the sludge up to 35 °C is given by the following equation [8]:

$$Q = W_f \Delta T (WC_{pw} + (1 - w)C_{ps}) \quad (6)$$

where Q is the required heat in kJ, W_f is the wet sludge weight in kg/d, C_{pw} is the water specific heat capacity (4.186 kJ/kg.°C), C_{ps} is the specific sludge heat capacity (1.95 kJ/Kg.°C), and ΔT is the temperature difference between sludge (at 18 °C) and the process temperature (35 °C). The heat value is equal to $0.7 \times 10^7 \ \frac{kJ}{d}$.

For heat value calculation, different surfaces should be checked separately (ceilings, exterior walls, basement walls, and floor), which have different parameters such as the material type, the thickness, surface area, type of insulator, etc. The heat required to compensate for the heat value is nearly 10 % of the heat required to increase the temperature of the sludge, and it is approximately $0.7 \times 10^6 \ \frac{kJ}{d}$. As a result, the total energy consumption is $0.78 \times 10^7 \frac{kJ}{d}$ and, according to the energy produced, the amount of recoverable energy is equal to:

$$E = 4.69 \times 10^7 \frac{kJ}{d} - 0.78 \times 10^7 \frac{kJ}{d} = 3.91 \times 10^7 \frac{kJ}{d} \quad (7)$$

Assuming that the efficiency of this method is 70 %, the net production energy is equal to $2.73\times 10^{7}\,\mathrm{KJ/d}$.

3.1.4. Greenhouse gas production by an anaerobic digester

Based on the previous section calculations, the production of biogas, including methane and CO_2, is 2291.9 m^3 /d, which contains 57.1 % methane, and the rest is CO_2. The methane flow rate is 1308.7 m^3/ d, and it is 983.2 m^3 /d for CO_2.

The global warming potential of methane is 21 times more than CO_2 over a period of one hundred years; thus, the equivalent CO_2 production of the dioxide is 27482.7 $\frac{m^3}{d}$.

$$V = 1308.7\ \frac{\mathrm{m^3}}{\mathrm{d}} \times\ 21 + 983.2 \frac{\mathrm{m^3}}{\mathrm{d}} = 28{,}466\ \frac{\mathrm{m^3}}{\mathrm{d}} \quad (8)$$

The total amount of greenhouse gas is 24866 $\frac{m^3}{d}$ and 18,140 ts annually.

3.1.5. Greenhouse gas emissions with energy recovery in the anaerobic digester

Methane combustion reaction is shown below:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (9)$$

The production of methane per year is about 18.955.377 mole; therefore, the same amount of CO_2 produced after burning is 834 t/y, while the primary CO_2 produced is equal to 626 t/y. As a result, the total production of greenhouse gases is 1,460 t/y. The calculation shows that the recovery of energy in the anaerobic digestion of sludge will prevent the annual entry of 16.680 ts of dioxin into the atmosphere, and the amount of pollutant produced in this way is 1.460 t/y.

3.1.6. Combustion energy efficiency

The energy generated from the combustion process involves the energy derived from the burning of dry sludge.

$$Q = 100\,\frac{\mathrm{m^3}}{\mathrm{d}} \times 58.14\,\frac{\mathrm{kg}}{\mathrm{m^3}} \times 15100\,\frac{\mathrm{kJ}}{\mathrm{kg}} = 8.78 \times 10^{7}\,\frac{\mathrm{kJ}}{\mathrm{d}} \quad (10)$$

The energy required for the combustion process includes the energy needed for sludge dewatering, an increase in the temperature of the sludge to reach the reactor temperature, and the energy losses caused by the radiation of the walls [9].

In order to reduce the amount of energy consumption in this process, it usually drains off the sludge with mechanical processes before heating up. In the process of centrifugal dewatering, there is a relatively large amount of investment, and it requires periodic maintenance. Pressure compression filtering has high capital investment cost and requires skilled labor. This method has also been implemented in a non-recurring manner and often requires mineral fertilizers to produce more material. The use of bulk filtering technology has lower cost for investment and energy consumption, and it is easy for maintenance. It was found that, by using the bulk filter process, the concentration of solids in the sludge reaches 20 % before entering the furnace for drying and burning [10,11]. The required energy for filtering by press is about 35 kWh/t DM. Regarding the flow rate and the solids content of the sludge, the amount of energy required for dewatering was estimated around 0.7×10^{7} kJ/d.

The energy required to evaporate the water in the sludge based on Equation (11) and the energy for increasing the temperature to 800 °C based on the Kim and Parker correlation were estimated 5 and 7, respectively [12].

$$Q_{drying} = M_{ws} \times W \times [(C_{p,water} \times \Delta T) + \Delta H_{vap}] + [M_{ws} \times (1-W)] \times C_{p,sludge} \times \Delta T \quad (11)$$

Q_{drying}: The amount of energy required to dry the sludge in terms of kJ/kg
M_{ws}: Sample weight of sludge [kg]
$C_{p,water}$: Specific heat capacity of water equal to 4.186 kJ/kg/C
ΔT: The difference of temperature from the environment temperature
ΔH_{vap}: The amount of energy needed to evaporate a kilogram of water is 2090 kJ/Kg
$C_{p,sludge}$: The sludge specific heat capacity equal to 1.95 kJ/Kg/C

$$Q_{target}=M_{ds}\times C_{p,sludge}\times \Delta T_{target} \quad (12)$$

Q_{target}: The amount of energy needed to increase the temperature of the sludge in terms of kJ/kg
M_{ds} : Weight of dry sludge per kg
ΔT: The temperature difference between the initial temperature (105 °C) and the reactor temperature (800 °C)

The heat loss of the furnace was also assumed to be 10 % of the energy used to evaporate and increase the water temperature, which was about $0.65 \times 10^7 \frac{kJ}{d}$. As a result, calculating the total energy consumed in the combustion process is equal to $7.84 \times 10^7 \frac{kJ}{d}$, and the production of recyclable energy is equal to $0.94 \times 10^7 \frac{kJ}{d}$; therefore, the efficiency of this method is 55 %. The net production amount is 0.51×10^7 KJ/d.

3.1.7. The amount of greenhouse gas produced in the burning method

The reaction to burning the sludge is as follows:

$$C_{34.8}H_{54.3}O_{14.3}N_{1.7}S_{0.38} + 41.6(O_2 + 3/76\ N_2) \longrightarrow 34.8CO_2 + 27.15H_2O + 0.38SO_2 + 157.28N_2 \quad (13)$$

The above equilibrium shows that, in this method, for the breakdown of 34.8 mole of organic carbon, 34.8 mole of greenhouse gas is produced. According to the calculations and sludge discharge of 100 m^3/d, the solid organic content is 4972.6 mole/d, which can produce 173048.2 mole of dioxin, which is equivalent to 7.6 t/d or 2,780 t/y.

3.2. Gasification

The energy generated in the gasification process consists of two parts; the first part is the energy generated from the synthesis of gases, and the other part involves recycling the energy from the hot gases of the outlet.

In the gasification process, sludge moisture needs to be reduced to 20 % before entering the process. It is assumed that the sludge will be dewatered to 80 % humidity by the process of belt press filtering and, then, the moisture content is reduced to 20 % by heat drying.

In this paper, a thermodynamic model is used to predict synthetic gases production. This model can be used to predict synthetic gases of various types of gasification. The thermodynamic model used has the following assumptions:

• The elements that make up the biogas are oxygen, carbon, hydrogen, and nitrogen and consume sulfur and other minerals.
• The reactor has enough retention time, and all carbon is converted into synthetic gases.
• Generated synthetic gases include CO, CO_2, H_2, CH_4, and N_2.
• The pressure drop is generated inside the gas-fired ignition system.
• The air-conditioning agent is used, and the reactor temperature is 1073 K [13].

The composition of the biomass reaction should be in the form of $CH_XO_YN_Z$; the global gasification reaction is as follows [14]:

$$CH_xO_yN_z + m_wH_2O + X_g(O_2 + 3.76N_2) \rightarrow X_1CO + X_2H_2 + X_3CO_2 + X_4H_2O + X_5CH_4 + \left(\frac{z}{2} + 3.76\,X_g\right)N_2 \quad (14)$$

where m_w is the number of water mole in the biomass, which can be calculated according to the following equation [14]:

$$m_w = \frac{M_{biomass} \times m}{18(1-m)} \quad (15)$$

In the above relation, m is the biomass moisture content.

X_g is the amount of air for the gasification reaction. The amount of air required for combustion of the entire biomass with $C_aH_xO_yN_z$ formulation is calculated according to Equation (16), which is o.3 for gasification [15].

$$Xg = 0.3 \times (a + 0.25\,x - 0.5\,y) \quad (16)$$

To obtain the coefficient of reaction, the following equation was used [14,15].

Carbon balance $X_1 + X_3 + X_5 = 1$ (17)

Hydrogen balance $2X_2 + 2X_4 + 4X_5 = X + 2m_w$ (18)

Oxygen balance $X_1 + 2X_3 + X_4 = y + m_w + 2X_g$ (19)

The thermal equilibrium of the chemical reaction is assumed to be:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (20)$$

$$C + 2H_2 \leftrightarrow CH_4 \quad (21)$$

The equilibrium constant for the two equations, given their molar composition, can be written as follows [14]:

$$K_1 = \frac{X_3X_2}{X_1X_4} \quad (22)$$

$$K_2 = \frac{X_5}{(X_2)^2} \quad (23)$$

Gibbs free energy is used to calculate K_1 and K_2 values [16]. The dry organic matter according to the standard form is as $CH_{1.56}O_{0.41}N_{0.05}$.

The coefficients of the elements in the reaction are obtained according to the calculations made by writing equilibrium equations, and the percentage of the gases formed are as follows:

X_1=0/692, X_2=0/598, X_3=0/215, X_4=0/287, X_5=0/092

$$CH_{1.56}O_{0.41}N_{0.05} + 0.29\,H_2O + 0.35(O_2 + 3.76N_2) \longrightarrow 0.692\,CO + 0.598\,H_2 + 0.215\,CO_2 + 0.287\,H_2O + 0.092\,CH_4 + 1.36\,N_2$$

CO = 25.91 %, H_2=1/6 %, CO_2 =12.65 %, H_2O = 6.9 %, CH_4=1.97 %, N_2 =50.95 %

Considering the above relation for each mole e of organic matter, 0.692 mole CO, 0.598 mole H_2, 0.215 mole CO_2, 0.287 mole H_2O, 0.092 mole CH_4, and 1.36 mole N_2 are produced. Bsaed on performed calculations, for each liter of sludge, 16.8 mole CO, 14.5 mole H_2, 5.22 mole of CO_2, 6.97 mole of H_2O, 2.23 mole of CH_4, and 33.05 mole of N_2 were produced.

The total synthetic gas produced according to the sludge discharge with a moisture content of 20 % and 7.12m^3/d is 119,762 mole CO, 103,494 mole of H_2, 37,209 mole of CO_2, 49,670 mole of H_2O, 15,922 mole of CH_4, and 235,488 mole of N_2. The generated synthetic gas heat will be equal to 5.76 $\frac{MJ}{n.m^3}$ according to the following equation [17].

$$LHV_g = Y_{CO}\,LHV_{CO} + Y_{H_2}\,LHV_{H_2} + Y_{CH_4}\,LHV_{CH_4} \quad (24)$$

where Y is the mole fraction of each gas, and also the thermal value of the gases is equal to:

LHV CO = 13.1 MJ/Nm^3
LHV H_2 =11.2 MJ/Nm^3

LHV CH_4 = 37.1 MJ/Nm^3

Given the thermal value of the synthetic gases and the amount of gas produced per day, the amount of energy generated by burning synthetic gases is equal to $7.2 \times 10^7 \frac{\mathrm{kJ}}{\mathrm{d}}$.

Another part of the energy produced in the gasification process involves the recovery of energy from the hot-gas in output. The outlet temperature is about 650 °C, which is reduced to 50 °C after thermal recovery. The amount of energy recovered from this section is equal to one kj/kg. By recycling the energy generated by cooling the synthesized gases[18], this energy is equal to $0.7 \times 10^7 \frac{\mathrm{kJ}}{\mathrm{d}}$.

3.2.1. Energy consumption in gasification

The energy used to prepare sludge for the process of gasification, including the amount of energy required to sink sludge to reach 80 % moisture and 20 % moisture, and the energy consumed in the process itself and increasing the temperature of the sludge until it reaches a furnace temperature up to 800 °C (1073 K), is equal to $7.12 \times 10^7 \frac{kJ}{d}$.

Renewable energy production is about 0.78×10^7 kJ/d. Assuming that the efficiency of this method is 80 %, the net energy produced by the process is around 0.62×10^7 kJ/d.

3.2.2. Greenhouse gas production by gasification

The total greenhouse gas produced in this method is 37.209 mol/d for CO_2 and 15.922 mol/d for CH_4, which is 5.975 ts annually based on the equivalent CO_2.

About 5.811.530 mol CH_4/y resulting from the same amount of CO_2 production after burning leads to 256 t CO_2/y. In addition, according to the CO burning reaction ($2CO+O_2 \rightarrow 2CO_2$), for 43.713.130 mol CO/y, the production for greenhouse gasses will be 1923 t CO_2/y. Therefore, the total amount of greenhouse gases produced after the energy recovery in the gas line is 2.776 ts/y. The calculation shows that the recovery of energy in the sludge gasification system results in 3.198 t annual decrease for CO_2, and the net production in this way is 2776 t/y.

3.3. Pyrolysis

In the pyrolysis process, the target is bio-oil production; however, in addition to bio-oil, other products, such as bio-coal, are also produced which, due to their special properties, improve the quality of soil and absorb pollutants less than the energy source used. In this paper, the energy from bio-coal is also included in the calculations.

The amount of bio-oil produced using the following experimental relationship was presented by Uchang et al., where $Y_{bio\text{-}oil}$ is the yields for bio-oil (%) and VS_{sludge} is the percentage of volatile solids in dry sludge, which is 30.5 % [9].

$$Y_{bio-oil} = 63.684 \times VS_{sludge} - 11.337 \qquad (25)$$

The percentage of bio-coal production in the process of rapid liquefaction with a moderate temperature is about 43 % of the sludge that contains 70 % of the solids. The thermal values of bio-oil and bio-coal produced are about 37.000 and 13.000 kj/kg.

Considering the percentage of products produced and their thermal value, the energy production was estimated [19].

$$Q = 30.5\,\% \times 5{,}814 \frac{\mathrm{kg}}{\mathrm{d}} \times 37{,}000 \frac{\mathrm{kJ}}{\mathrm{kg}} + 43\,\% \times 5{,}814 \frac{\mathrm{kg}}{\mathrm{d}} \times 13{,}000 \frac{\mathrm{kJ}}{\mathrm{kg}} = 9.8 \times 10^7 \frac{\mathrm{kJ}}{\mathrm{d}}$$

3.3.1. The energy consumption for pyrolysis

The energy required for sludge water evaporation and temperature increases to reach the reactor condition (500 °C). According to the Caballero tests and colleagues (1998), energy production was considered to be 300 kJ/kg-ds[20].

The amount of energy lost during the pyrolysis process is 10 % of the total energy used [12]; hence, the total energy consumed is equal to $7.5 \times 10^7 \frac{kJ}{d}$.

$$Q_{total} = Q_{drying} + Q_{target} + Q_{pyrolysis} + Q_{loss} \quad (26)$$

Based on Equation (26), the total energy was estimated to be about $2.3 \times 10^7 \frac{kJ}{d}$.

Assuming that the efficiency of this method is 90 %, the net energy produced is equal to $2.07 \times 10^7 KJ/d$.

3.4. Comparison of methods for energy production

The data are given in Table 2 and Figure 1.

Table 2

A summary of results for energy balance.

Process	Energy consumed ($\frac{KJ}{d}$)	Generated energy ($\frac{KJ}{d}$)	Renewable energy ($\frac{KJ}{d}$)	Net energy production ($\frac{KJ}{d}$)
Combustion	7.84×10^7	8.78×10^7	0.94×10^7	0.51×10^7
Pyrolysis	7.5×10^7	9.8×10^7	2.3×10^7	2.07×10^7
Gasification	7.12×10^7	7.9×10^7	0.78×10^7	0.62×10^7
Anaerobic digestion	0.78×10^7	4.69×10^7	3.91×10^7	2.73×10^7

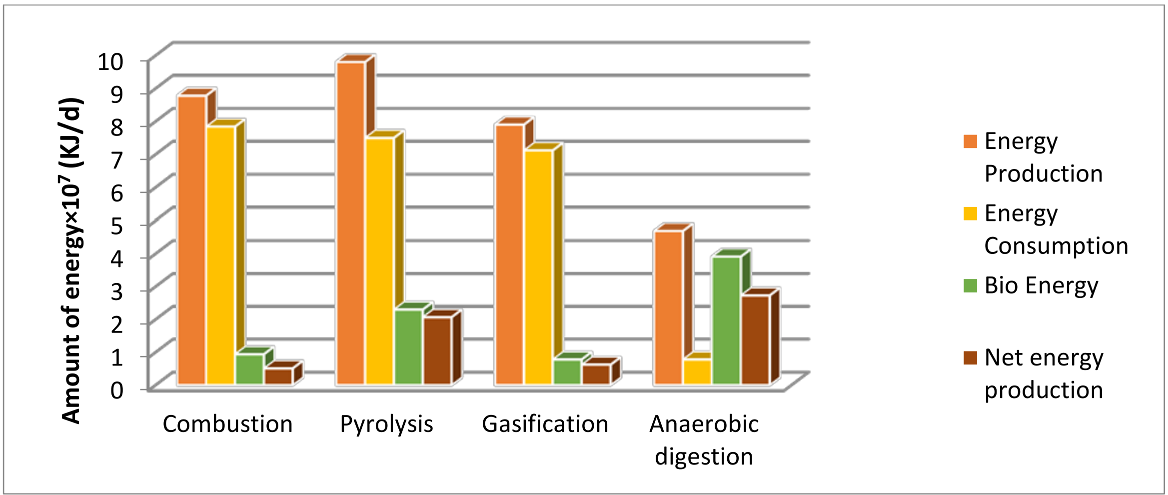

Figure 1. Comparison of energy efficiencies.

3.4.1. Reducing the effect of global warming

The production of greenhouse gases in an anaerobic digester is 1.460 ts annually, and this is 2.780 and 2.776 ts in combustion and gasification methods, respectively. Therefore, the digestion is the best option environmentally, which will lead to less greenhouse gas production.

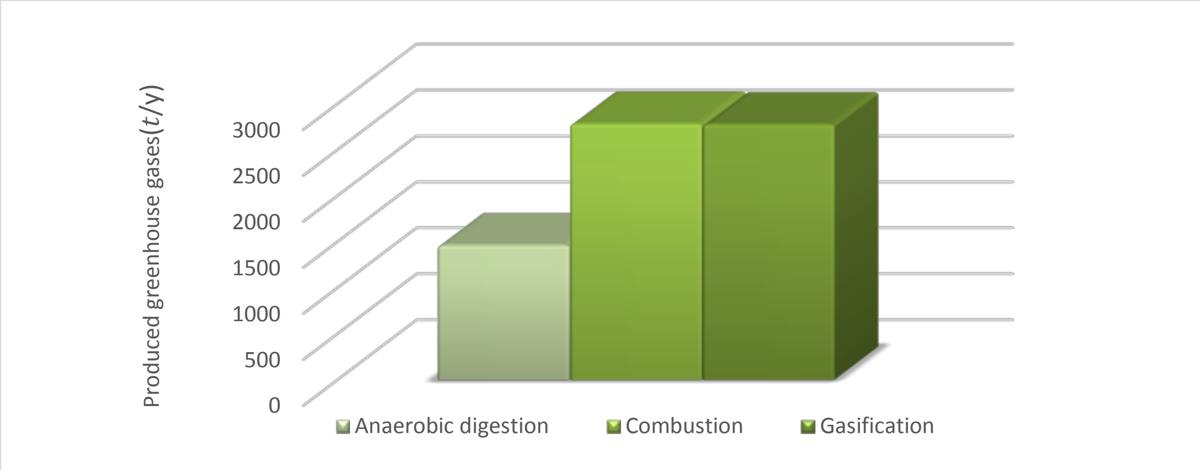

Figure 2. Comparison of greenhouse gas emissions.

3.4.2. Power plants feasibility study

In order to estimate the capacity of the constructed power plant at the Ekbatan sewage treatment plant site, the amount of the biogas extracted from the treatment unit was estimated. Among the primary stimuli for producing electricity from biogas, biogas engines are selected because they have better access to other technologies in the country and have a decent return on low capacities. These engines are available at less than 1 MW capacity and are economically feasible [21].

The amount of biogas produced from digestion is 2291.9 m^3/d. By using the following equation, the amount of electricity generated per cubic meter of biogas is calculated:

$$\frac{1\text{m}^3 \times 0.571 \times 0.4 \times 35{,}850\,\frac{\text{kJ}}{\text{m}^3}}{3{,}600\,\frac{\text{s}}{\text{h}}} = 2.27\ \text{kWh}$$

In the above correlation, 0.571 is the percentage of methane in the biogas, and 0.4 is the efficiency of the biogas engine; therefore, the biodiesel engine produces 2.27 kWh of electricity per cubic meter of biogas. The production of biogas from the digester is 95.5 m^3/h; thus, the power of the plant is equal to 216.8 KW.

Since the average temperature of the treatment plant is 18 °C and the average height of the construction site of the treatment plant is 1.020 m, the power output of this generator motor is reduced by 4 %, as shown in Table 3, which is the effect of temperature and height on the performance of the generator engine [22].

Table 3
The effect of temperature and height on the efficiency of the engine [22]

Height (m)	**Temperature (°C)**				
	25	30	35	40	45
500	1	0.99	0.98	0.97	0.96
800	0.98	0.96	0.96	0.95	0.94
1100	0.96	0.95	0.94	0.93	0.92

Normally, 20 % overestimate is expected for plant design; therefore, the capacity of the plant is 260.2 kW. As a result, two 160 kW biogas generators can be used to maintain a power plant with about 60 % capacity in the case of repairing one of the generators.

Assuming that the power factor is 90 %, the power plant is capable of operating 328 days a year; then, the annual energy production by the power plant is equal to:

$$216.8\ \text{KW} \times 0.9 \times 8760\frac{\text{h}}{\text{year}} = 1{,}533{,}643\ \text{kwh}$$

This power plant generates 1533643 kwh of electricity worth of 150,000 $, which can meet the treatment plant's demands and buy the excess part by the Ministry of Energy. (with the inquiry from the Iran Ministry of Energy, the purchase cost per kilowatt-hour is 10 cents).

3.5. Economic review of the plant

The fixed capital investment is shown in Table 4.

Fixed capital cost of plants is about 2.1 million $, which is an extra cost for digester and 40 % for other plants, including converters, digesters, tanks adsorption towers, compressors, burners, etc. In addition, 15 % for biogas purification system, 10 % for design and commissioning, and 5 % for maintenance costs are also calculated [21].

The total estimated cost for the construction of manure and the 320 kW biogas plant is more than million dollars. Considering that the annual electricity generation of the power plant is 1.533.643 kw/h, the annual electricity production for power plant is worth 1.5 million $, for return time of 30 months.

Table 4
Fixed capital cost for the construction of a biogas plant.

The cost of purchasing any 160 kW generator engine	120 thousands $
Customs fee	4 % The cost of buying generators
Trans cost	7-9 thousands $
The cost of establishing silos	14-20 thousands $
Cabling	5-6 thousands $
Accessories (including plumbing, fan sucker and blower, oil tank, fuse, etc.)	16-20 thousands $

4. Conclusions

The results of the calculations in this paper showed that although the energy produced from the digestion process is lower than other processes, its pure net production is significantly higher due to the low energy consumption.

With a study for Ekbatan's treatment plant, the unit with a 4.500 m^3/d in volume could produce 2291.9 m^3 of biogas per day and 1308.6 $m^3$of methane.

Greenhouse gas production in an anaerobic digestion process is 1460 t/y, and it is 2.780 and 2.776 t/y in burning and gasing methods, respectively. It was concluded that anaerobic digestion was the most appropriate option environmentally due to its lower emissions of greenhouse gas.

Energy recovery of sludge in anaerobic digester will prevent the entry of 16.680 ts of CO_2 into the atmosphere annually.

The annual production of biogas from quicklime is 836.543 m^3 with a flow rate of 4.500 m^3/d. The thermal value of this biogas is equal to 475.514 m^3/y. This biogas can be used to supply heat for sludge handling or other treatment units. Therefore, with the proper utilization of the treatment plant, the annual consumption of 475,514 m^3 will be saved on natural gas consumption.

The resulting biogas can also be used to generate power. Surveys show that a power plant with a capacity of 260.8 kw of electricity can be built up with a biogas generator engine at the treatment plant site; therefore, two engine gas generators with a capacity of 160 kw were proposed.

The potential power plant will be able to produce 1.533.643 kWh of electricity worth of 1.5 million dollars, which can meet the needs of the treatment plant, and the excess will be sold to the Ministry of Energy.

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