

Using Biomass in Power Generation for Supplying Electrical and Thermal Energy in Iran and Evaluation of Environmental Pollution Spread

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Abstract: The main objective of this study is estimating environmental pollution of hybrid biomass and co-generation power plants. Efficiency of direct tapping of biomass is about 15%-20%. Consequently, about 80% of energy would be waste in this method. While in co-generation power plant, this number could improve to more than 50%. Therefore, to achieve higher efficiency in utilizing biomass energy, co-generation power plants is proposed by using biogas as fuel instead of natural gas. Proposed system would be supplied thermal and electrical energy for non-urban areas of Iran. In this regard, process of fermentation and gas production from biomass in a vertical digester is studied and simulated using analytic methods. Various factors affecting the fermentation, such as temperature, humidity, PH and optimal conditions for the extraction of gas from waste agriculture and animal are also determined. Comparing between the pollution emission from fossil fuel power plants and power plants fed by biomass shows about 88% reduction in greenhouse emission which significant number.

Key words: Biomass energy, digestion, co-generation power plant, biogas, environmental pollution.

Nomenclature

CHP	Combined heat and power
ODM	Organic dry matter
HV	Heat value
V_{biogas}	Volume of biogas
$\frac{dx}{dt}$	Net growth rate of microorganisms (kg/(m ³ ·s))
$\frac{df}{dt}$	Rate of materials used in the digester (kg/(m ³ ·s))
X	Density of microorganisms in the digester (kg/m ³)
a	Resultant growth factor
b	Microorganisms decay coefficient (1/s)
S	Concentration (kg/m ³)
K	Rate of weight loss by microorganisms (kg/(m ³ ·s))
K_s	Density of unused material (kg/m ³)
ζ	Efficient of waste use (0.9-0.6)

Q	Flow rate (m ³ /day)
P_x	Net mass of release cells (kg/day)
S_0	Density of remain material (gr/m ³)

1. Introduction

Nowadays, electricity production faces with so many challenges. Control and protection, efficiency of small and large customer consumption and demand response would face with new issues with high penetration of renewable energies [1-3]. High costs, pollution and limited resources of fossil fuels are main motivations for using renewable sources to fulfill the energy needs [4-6]. Biomass is one of the main sources of renewable energy. Biomass term used to describe a series of products that are obtained from photosynthesis. The most common sources of biomass are agricultural waste, forest, food, municipal solid

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waste, sewage, water plants and waste from wood processing. The main aspect of biomass compared to other renewable energy sources is the availability of it. Despite wind and solar which their availability depends on environmental and weather condition, biomass is local renewable resource that using its energy does not need any complex technology, and it is so compatible with most of current fossil fuel power plants. Some other advantages of biomass energy are [7]:

- disposal of a huge amount of organic waste and recovering energy from it;
- animal manure could also be utilized as fertilizer in agriculture;
- political issues related to fuel dependency of countries;
- decrease of the odor problem;
- economic and social development in rural areas;
- provides new job opportunities.

Bioenergy is the largest global source of renewable energy, and contributes an estimated 10% of global primary energy production, in particular as a direct source of industrial and domestic heat [8]. Most of this is consumed in developing countries for cooking and heating, using very inefficient open fires or simple cook stoves with considerable impact on health (smoke pollution) and environment (deforestation). Modern bioenergy supply on the other hand is comparably small, but has been growing steadily in the last decade. In the buildings sector, modern bioenergy use for heat reached around 5 EJ in 2012. In addition, 8 EJ were used in industry, mainly in the pulp and paper as well as the food processing sector, to provide low and medium temperature process heat. Furthermore, a total of 370 TWh of bioenergy electricity was produced in 2012. This corresponds to 1.5% of world electricity generation.

Biomass can be formed into solid, liquid and gas and be used as energy source directly, but the conversion of biomass to gas, as biogas is better method since it has higher heating value than other types of biomass fuel [9]. Biogas first had used in

Assyria to heat the bath water about 10 centuries BC. The first anaerobic digester was built in 1859 by the leper colony in Bombay. In 1879, that gas production from waste was discovered, digester was used in Britain as source of energy as well. Anaerobic fermentation was recognized as a science in 1930 and research to investigate the factors influencing the growth of bacteria methane took place [10]. In this study, hybrid system using biomass and co-generation power plants (combined heat and power—CHP) is proposed for supplying electrical and thermal energy need in Iran and release of environmental contaminants is investigated.

2. Potential of Biomass in Iran

Biogas sources in Iran are divided into four groups [11]:

(1) Agricultural residue and waste

In the year 2010-2011, almost 75.4 million ton of crops have been harvested from arable land in Iran. If the average losses of these products are considered to be 30%, the amount of waste produced for 1 year is about 23 million ton [12]. If it is assumed that, an average of 450 m³ of biogas is produced from each ton of waste, about 10,350 million m³ biogas will be generated from agriculture waste.

(2) Municipal solid waste

Percentage of organic waste in municipal solid waste in Iran is about 75%. Using anaerobic digestion, most of the organic material in the waste is decomposed and biogas is produced by anaerobic bacteria fermentation. In Iran, for every person, an average of 0.8 kg of waste is produced every day. About 40-50 thousand tons of waste is produced per day in Iran and since 1 m³ of biogas is obtained per 15 kg of solid waste, 841 Petajoules of energy can be generated from solid municipal waste in Iran [11].

(3) Solid and liquid perishable industrial waste

Industrial wastes such as food and wood industries can also be used to produce biogas. Biogas from industrial waste water is highly variable. This quantity

depends on the type of industry, the type of waste water refinery process and quantity of waste water. For example, annually 81.5-279.4 million m³ of biogas can be obtained from food industries in Iran [11].

(4) Livestock wastes

Livestock wastes have considerable potential to produce biogas. Annually 74 million ton methane gas is produces from livestock manure in Iran [13]. According to the data released, there are 24,659 animal husbandry with 2,747,124 cows in 2011 in Iran [14]. There are approximately 72 million livestock in Iran [15]. Annually 74,964 ton of animal wastes are available in Iran from which 8,668 million m³ of biogas can be produced [16].

Recently, in addition to academic and research centers, Iran has constructed and operated some pilot power plant using biomass as fuel as well. Some of the examples are: Shiraz, Mashhad, Isfahan, Saveh and Tehran.

3. The Fermentation Process and the Factors Affecting It

3.1 Digestion

Anaerobic digestion is fermentation of organic matter by the yeast bacteria. This process produces a gas that is typically 65% methane and 35% CO₂, with components such as sulfur compounds, nitrogen, hydrogen, organic acids and ammonia. The resulting gas can be burned directly in boilers or internal

combustion engines used for the operation. Calorific value of obtained gas from biomass is often between 17 and 325. Typically, 40%-60% of organic material in the digester turns to biogas. The remaining material consists of a rich fertilizer and without annoying odor that is used to improve agricultural soils [17]. During the fermentation process, complex organic materials are converted into simple organic compounds and acids, then methane bacteria of acetic acid would converted material to methane and CO₂. Process of digestion is shown in Fig. 1 using Ref. [18].

3.2 Digester

One of the most important equipments for a biomass gasification is digester. Digester capacity to be installed in rural areas depends on parameters such as population and the minimum energy requirement. Digester should be in place between the consumer and the collected biomass. Digester must be installed in cylindrical with outer diameter slightly greater than the inner diameter. During drilling, the two split in two different directions with a slope of 45 degrees for feeding and discharging the digester should be considered. The outer wall of a brick digester should be made with no gaps that cause gas leaks [19]. The schematic of a digester is shown in Fig. 2.

3.3 The Governing Equations of Anaerobic Fermentation

The rate of growth of yeast bacteria:

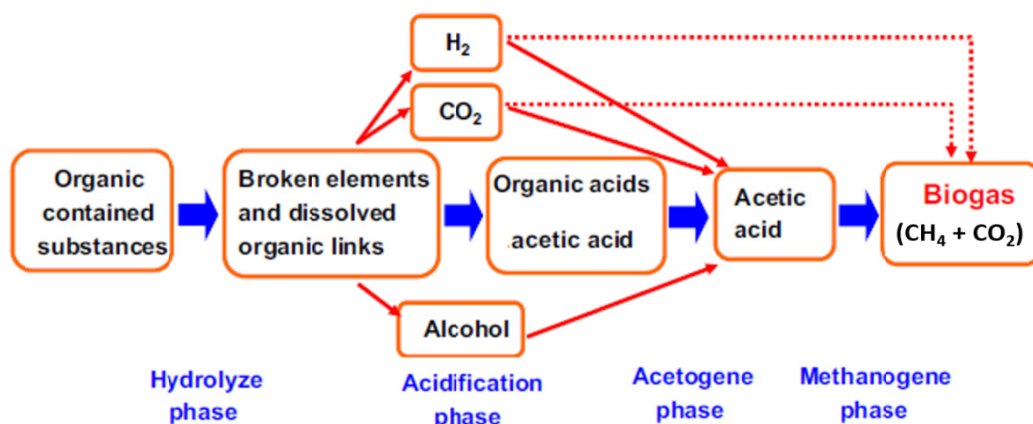


Fig. 1 The anaerobic disintegration phases of organic substances.

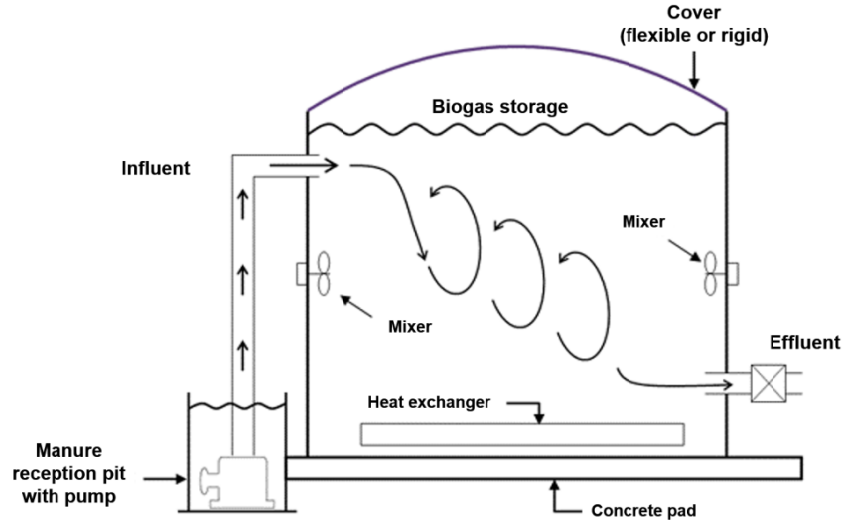


Fig. 2 Digester.

$$\frac{dX}{dt} = a \cdot \left(\frac{dF}{dt} \right) - b \cdot X \quad (1)$$

$$\frac{dF}{dt} = \frac{K \cdot S}{K_s + S} \quad (2)$$

Constants of a , b and K would be calculated using experimental data. Volume of produced methane gas can be found using Eq. (3):

$$V_{CH_4} = 0.35[(EQS_0) - 1.42(P_X)] \quad (3)$$

After defining the daily volume of produced biogas, required volume of digester would be designed based on gas volume and mass of remain material on digester each day.

3.4 Factors Affecting Anaerobic Fermentation

Temperature: Methane bacteria in the range of mesophilic and thermophilic which is generally between 45-65 °C and 26-43 °C, respectively is very active. Although mesophilic range is more common due to the ease in providing. Fig. 3 shows effect of temperature on biogas production [20].

Acid level (PH): Methane formation is very sensitive to level of acidity. If PH is less than 6 or more than 8, the production of methane gas would be stopped. Fig. 4 shows the effect of PH on gas production [19].

Concentration: Solid concentration must be 7%-9% for the following reasons [20]:

- To prevent mud formation on top of digester;
- Facilitate the movement of matter in the digester.

Storage time: Enough time should be given to the material in the digester to allow full metabolized by bacteria in the digester.

The ratio of carbon to nitrogen: ratio of carbon to nitrogen in the range of 20-30 is considered as a suitable for fermentation.

In Fig. 5, the variation of the gas produced during fermentation is shown. Generally, biomass volume reach to its maximum level every 20 days.

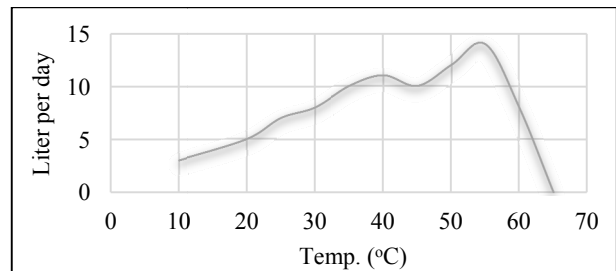


Fig. 3 Effect of temperature on gas production.

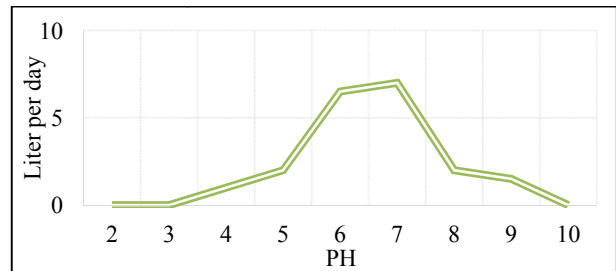


Fig. 4 Effect of PH on gas production.

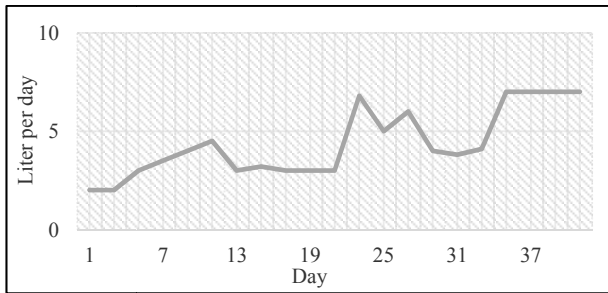


Fig. 5 Biogas production during fermentation process.

4. Co-generation Power Plant

4.1 Motivation

Fig. 6 is shown that, use of biogas in concurrent production power plant compared with separate production of electrical energy and heat will cause 40% fuel reduction and consequently efficiency would increase.

4.2 Equations

The amount of steam produced in a co-generation power plant is dependent on temperature of the input

gases to the heat recovery boiler. If temperature of the inlet gases to steam boilers increase, production value will increase. Using the equation of energy flow, the amount of steam produced survival in heat recovery boilers is calculated [21]. Fig. 7 shows flow of product steam based on gas turbine capacity.

$$\text{Steam (ton/hr)} = 1.96P \text{ (MW)} + 1.78 \quad (4)$$

By increasing capacity of gas turbine, in addition to flow of steam production, efficiency would improve as well. Fig. 8 shows efficiency of gas turbine based on its capacity.

$$\text{Efficiency (\%)} = 0.0144 \ln(P \text{ (MW)}) + 0.2864 \quad (5)$$

Increasing capacity of gas turbines leads to other consequences as well. On one side, boosting the capacity of gas turbines means that, the amount of gas input increases, on the other hand, required inlet gas pressure should be raised. These two parameters are considered as limiting factors to increasing the

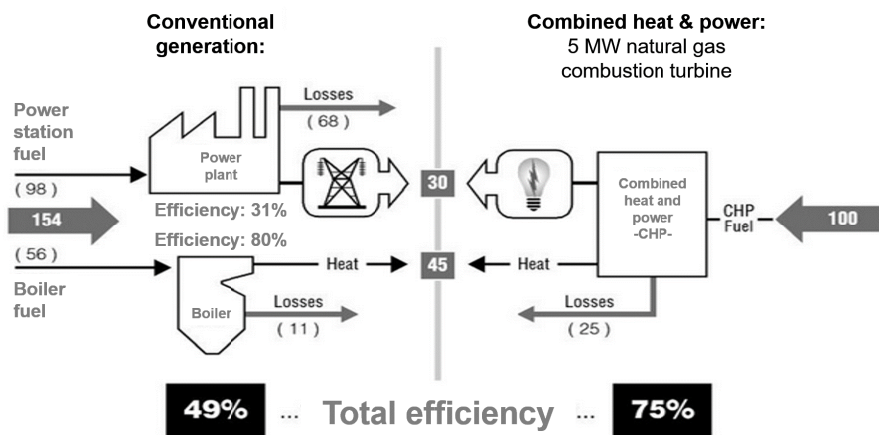


Fig. 6 Comparing co-generation and separate generation.

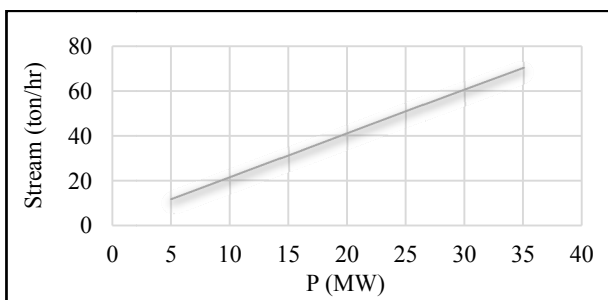


Fig. 7 Flow of produced steam based on gas turbine capacity.

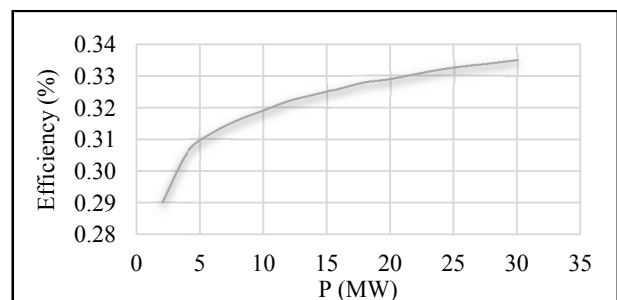


Fig. 8 Efficiency of gas turbine based on its capacity.

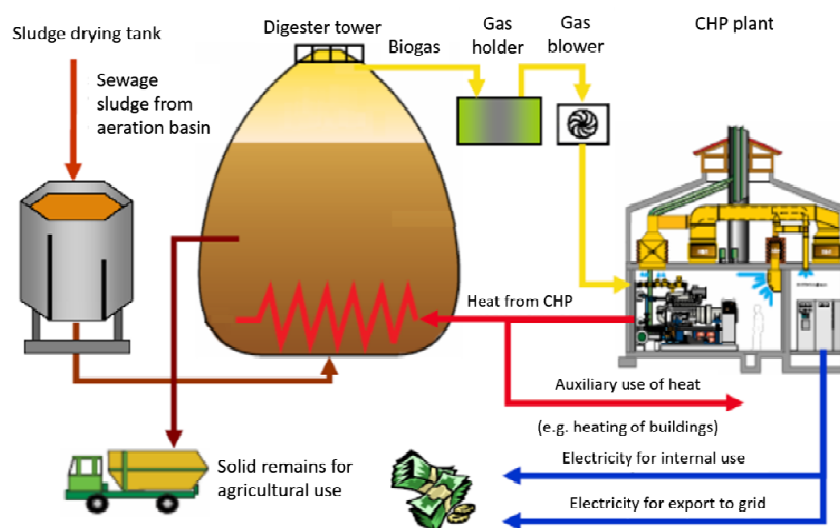


Fig. 9 Schematic of CHP power plant fed by biogas.

capacity of gas turbines, especially since the amount of gas produced depends on the amount of available biomass. For example, if the gas turbine capacity increased from 5 MW to 10 MW, required gas pressure changes from 16 psig to 250 psig. Assuming that, 60% of natural gas is methane gas, required gas from the fermentation changes from 7,800 m³ to 15,000 m³ change, which is significant change. Fig. 9 [4] shows a schematic of co-generation power plants fed by biomass. After cleaning process, biogas is transferred to the combustion chamber of a gas turbine, the output heat then would goes to steam plant cycle.

5. Evaluation of Pollution Spread

CHP is generally using less fuel to produce electrical and thermal energy simultaneously in compare with individual energy producing plants. When less fuel is used to meet thermal and electric power needs, fewer air pollutants and greenhouse gases are emitted. Comparison between fuel consumption and pollution emission of CHP and separate power plant is shown in Table 1. Similarly, when natural gas or renewable, sustainable -produced biomass fuels displace the use of fossil coal or petroleum, emissions can be further reduced. DOE estimates that, the current fleet of CHP systems saves about 1.8 quads of energy annually and reduces U.S. carbon dioxide emissions by 240 million

metric tons, the equivalent of removing 40 million cars from the road. Installing another 40 GW of CHP could further reduce CO₂ emissions by 150 million tons per year, the equivalent of removing another 25 million cars from the road [22].

When biomass is produced sustainable, biomass-fueled CHP systems can produce heat and power with very few net greenhouse gas emissions, and thus can be much more climate-friendly than systems fueled with fossil natural gas, coal, or oil. By substituting biomass for fossil fuel, carbon emissions from non-renewable, finite fossil fuels can be avoided. Further, because almost all of the biomass used for biomass CHP today is derived from forestry or agricultural residues or urban waste streams, significant additional emissions of climate-changing methane, which would otherwise be released to the atmosphere from decomposition, are avoided. The avoided methane emissions can actually make some

Table 1 Comparison of CHP and individual power plant.

Emission (ton/year)	CHP	Electrical energy	Thermal energy
NO _x	20.35	43.58	12.90
SO ₂	0.13	105.87	0.08
CO ₂	25,885	43,432	15,078
CH ₄	0.49	0.496	0.28
N ₂ O	0.05	0.713	0.03

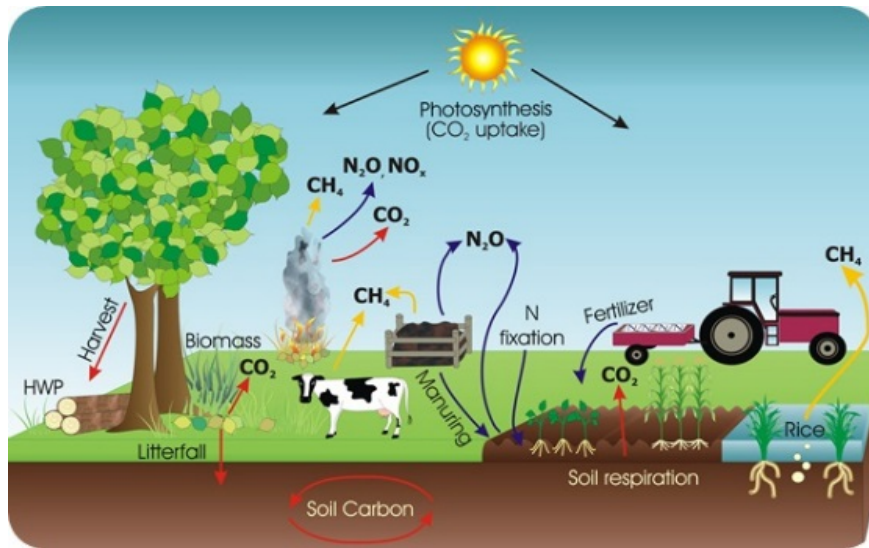


Fig. 10 Emission cycle of biomass.

renewable biomass CHP systems net carbon negative on a life cycle basis. In Fig. 10, it is shown how emission of biomass would be decrease in cycle of production and consumption of biomass.

6. Case Study

In this section, an example of the CHP with biogas fuel consumption is discussed to supply electrical and thermal energy of 10 assumed rural home in Iran. Required thermal and electrical energy of these houses is shown in Fig. 11.

For biomass source, energy crops are used that are production that specifically cultivate to use as energy resource [23, 24]. Required mass of biomass fuel and capacity of digester is designed using equations of subsection (Section 3.3). Capacity of CHP and its efficient is also calculated using equations of subsection (Section 4.2). Input data of case study is shown in Table 2.

Process that should be analyzed in digester includes balance of mass and energy. For charging 50 tons of input to digester each day, mass balance would be as in Table 3.

Energy calculations for anaerobic digester include: The fuel gases from biomass, converting gases into useful energy, input heat to digester.

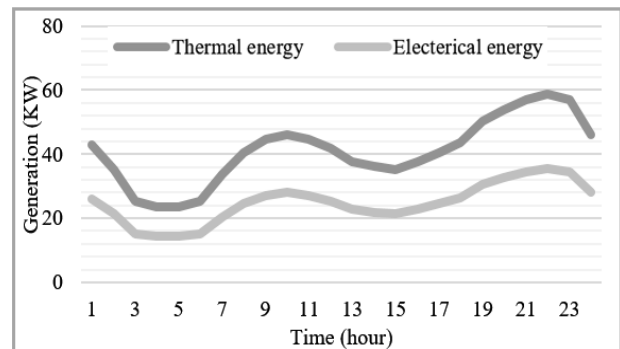


Fig. 11 Electrical and thermal energy of case study.

Table 2 Input data.

Mass of dry biomass	15 ton/day	Capacity of digester	3,000 m ³
Mass of water	35 ton/day	Area of digester	1,000 m ²
Methane in biogas	60%	Insulation thickness	0.1 m
HV of methane	35.7 MJ/m ³	Insulation conducting	0.035 W/(m ² ·°C)

Table 3 Mass balance in digester.

H ₂ O	Ash	ODM	
35 ton/day	1.5 ton/day	13.5 ton/day	
End of digestion			
H ₂ O	Ash	ODM	Biogas
35 ton/day	1.5 ton/day	4.5 ton/day	9 ton/day

Heat value of methane is 35.7 MJ/m³ as it shown in Table 2. Stoichiometric equation for combustion of 1 m³ of biogas, consisting of 60% methane, 40% carbon dioxide and 1,000 ppm sulfuric acid is as follows:

$600 \text{ lit CH}_4 + 400 \text{ lit CO}_2 + 1 \text{ lit H}_2\text{S} + 1,201.5 \text{ lit O}_2 \rightarrow 1,000 \text{ lit CO}_2 + 1,201 \text{ lit H}_2\text{O} + 1 \text{ lit SO}_2 + 21.4 \text{ MJ}$ (6)

In our case study, biogas production is $7,500 \text{ m}^3/\text{day}$, that consequently:

In CHP, $1,860 \text{ kW}$ gas would be turned into 595 kW of electrical energy considering 32% efficiency and 985 kW of thermal energy would also produce. Temperature of inlet heat of digester depends on waste heat and required energy for increasing temperature of material. Waste heat could be defined based on digester area and conducting insulator. Assuming 37°C temperature of inside temperature and 5°C for outlet air, heat waste could calculate as follows:

Required heat energy to increase temperature of digester is equal to mass of input material by temperature difference. In our case study that 50 ton day with 10°C are injected to digester and should reach to 37°C degree, heat energy would be determined as follows:

Therefore, total required heat energy is:

Summary of output results is shown in Table 4.

Comparison between pollution emission of CHP using fossil fuel and biomass is shown in Fig. 12. As it shown for producing same amount of electrical and thermal energy, using biomass leads to huge reduction of greenhouse gas emission in compare with fossil

Table 4 Output parameter.

Mass of biogas	9 ton/day	Electrical energy	595 kW
Volume of biogas	$750 \text{ m}^3/\text{day}$	Thermal energy	985 kW
Total energy of biogas	$1,860 \text{ kW}$	Total heat energy	76 kW

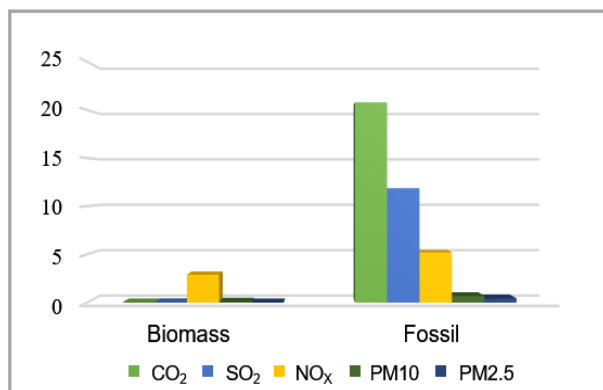


Fig. 12 Pollution emission of biomass vs. fossil fuel.

fuel. These reduction would be huge different in one year and could answer many of global warming concerns.

7. Conclusions

The conversion of biomass to gas in the digester is the traditional approach to extract energy from biomass as it discussed in this paper. In this way, an anaerobic digester can be installed near the site of collected biomass that can be agricultural waste, animal manure or energy crops. Suitable fermentation conditions such as temperature, humidity and PH is discussed in this study. Biomass would convert after 20-40 days to gas that contains 40-60 percent of methane. The resulting methane gas would be cleaned to be ready for combustion in CHP power plant that could supply electrical and thermal energy of non-urban area. Extracting energy of biomass in CHP power plant would not produce any carbon dioxide and sulfured emission and would only lead to small emission of NO_x components. Therefore using hybrid of CHP/ biomass has 88% less pollution emission and more environmental friendly source.

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