Applied Thermal Engineering 128 (2018) 1543–1554

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Effects of fuel composition on the economic performance of biogas-based power generation systems

Hasan Barzegaravval [a,*], Seyed Ehsan Hosseini [b], Mazlan Abdul Wahid [a], Aminuddin Saat [a]

[a] *High-Speed Reacting Flow Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*
[b] *Department of Mechanical Engineering, Arkansas Tech University, 1811N Boulder Ave, Russellville, AR, 72801, USA*

HIGHLIGHTS

- Exergo-economic analysis of a biogas-based gas turbine with preheater is performed.
- Efficiency falls by 0.5% and total cost rate increases by 1% when fuel composition changes.
- Different fuel pricing strategies are implemented and results are compared.
- Cost of power varies from 0.05 to 0.18\$/kWh for different fuel cost and system size.
- Economic performance is introduced and evaluated at around 63%.

ARTICLE INFO

Article history:
Received 13 March 2017
Revised 15 September 2017
Accepted 21 September 2017
Available online 22 September 2017

Keywords:
Biogas gas turbine
Exergy
Economic
Fuel composition

ABSTRACT

Biogas to fuel is an attractive method to reduce global warming potential of methane emission and providing a renewable source of energy. In this study, exergoeconomic assessment of a biogas-based gas turbine system with preheater is conducted. In the present work, effects of fuel composition on the exergetic and economic performance of a plant are studied, and comparison between two fuel pricing methods has been carried out. Fuel composition effects have not been studied before and fuel pricing mostly conducted in terms of lower heating value (LHV) in previous studies. In this study, percentage of methane content in the fuel is changed. Two definitions for fuel pricing are used, one based on the exergy and the other based on the LHV of the biogas and the results are compared. In addition, the cost factors are defined and the cost of generated power are evaluated. To add more generality to the work, system sizes ranged from 1 to 10 MW is taken into consideration to understand the effect of system size as well. Results reveal that fuel pricing based on the exergy gives more realistic evaluations. Furthermore, when methane content is changed from 0.95 to 0.6, total cost rate of the plant rises around 1% and electricity cost augments. Exergetic efficiency mitigates when methane content reduces. Based on the system size and biogas fuel price, the cost of generated electricity varies from 0.05\$/kWh to 0.18\$/kWh in this assessment.

1. Introduction

Global warming and energy resources depletion are among main concerns of human beings. Greenhouse gases (GHG) are known responsible for increasing trend of the planets' temperature globally. Methane (CH_4) shows high greenhouse effects, much higher than carbon dioxide (CO_2) and according to International Panel on Climate Change (IPCC) report [1], its global warming potential is 25 times greater than CO_2 in mass basis. A significant source of methane emission is biomass and wastes digested by bacteria's, especially livestock and agricultural wastes [2,3]. Preventing methane emission from natural sources is crucial in environmental protection and global warming control. One method to reduce the emission impact and eliminate the methane emission is capturing produced methane rich gas mixture, which is called biogas, and utilize it as a source of fuel. Produced gases from anaerobic digestion is a source of CH_4. Nevertheless, despite of its environmental negative effects, this so-called biogas can be a source of green energy. In fact, using biogas as a source of energy has three advantages [4]:

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* Corresponding author.
E-mail address: hasan.barzegar.a@gmail.com (H. Barzegaravval).

https://doi.org/10.1016/j.applthermaleng.2017.09.109
1359-4311/

Nomenclature

$\dot{C}$	cost flow rate (\$/s)
C_{factor}	cost factor (1/s)
Ex	exergy flow rate (kW)
ex	exergy (kJ)
$E\dot{x}d$	exergy destruction rate (kW)
FP	fuel Price (\$/GJ)
h	enthalpy (kJ)
$\dot{m}$	mass flow rate (kg/s)
M	molar mass vector for species in a composition (kg/kmol)
M_t	molar Mass of a composition (kg/kmol)
P	pressure (bar)
r	pressure ratio
R	gas constant (kJ/kmol-°K)
T	temperature (°K)
$\dot{W}$	power or Work (kW)
X	carbone dioxide molar concentration in biogas (%)
Y	molar concentration vector of species in a composition (%)
Z	purchase cost of components (\$)
$\dot{Z}$	purchase cost rate of components. (\$/s)

Greek letters

α_0	cost factor (change in total cost rate) with fuel pricing in LHV (%)
α_1	cost factor (change in total cost rate) with fuel pricing in Total Exergy (%)
α_g	mass factor (change in mass flow rate of flue gases inters the gas turbine) (%)
α_Z	purchase cost factor (change in Total Purchase cost of components) (%)
β_0	ratio of fuel chemical exergy to LHV
β_1	ratio of fuel total exergy to LHV ratio
η	efficiency
η_{eco}	economic efficiency or performance

Subscripts

a	air
CH	chemical
ex	exergetic
g	flue gases
f	fuel
ph	physical

Abbreviations

AC	air Compressor
AP	air Preheater
CC	combustion Chamber
CHP	combined Heat and Power
GT	gas Turbine
IPCC	intergovernmental Panel on Climate Change
IRR	internal Rate of Return
MGT	micro Gas Turbine
NPV	net Present Value
NRCS	natural Resources Conservation Service
NREL	national Renewable Energy Laboratory
ORC	organic Rankine Cycle
SOFC	solid Oxide Fuel Cell
TIT	turbine Inlet Temperature

- Biogas is a renewable energy.
- Biogas oxidation generate energy and replaces methane with CO_2. The latter has much lower greenhouse effect.
- Biogas from waste materials, has low net CO_2 emission since it produces from natural organic disposals.

Due to aforementioned reasons, biogas utilization for energy generation purposes has attracted attentions. Li, et al. [5], studied the potential of biogas production from livestock wastes and poultry breeding in rural areas in China and potential of biogas generation and emission reduction were estimated as 20% of natural gas consumption and emission reduces about 220 million tons annually. Uddin et al. [6], investigated the potential of using biogas for power generation in Pakistan and discovered a potential of 35.63 GWh of electricity per day in livestock sector which is enough to overcome the energy crisis in Pakistan. Abdeshahian et al. [7], studied the potential of biogas generation in Malaysia from animal wastes using anaerobic digestion plants and estimated that 8.27 TWh electricity per year can be generated. Santos et al. [8] performed economic feasibility study on electricity generation using biogas generated from wastewater treatment facilities in Brazil and concluded that the plan is feasible for cities with populations greater than 300,000. Rios and Kaltschmitt [9], study showed that average power generation potential of 6.40 TWh could be available in 391 municipalities in Mexico.

1.1. Multigeneration with biogas

To improve the efficiency of various systems, multigeneration energy systems were proposed. Speidel et al. [10] proposed a new integration system for gasification process coupled with a power generation system. A configuration of sludge fermentation process, solid oxide fuel cell (SOFC) and gas turbine and gasifier was assessed in terms of energy. It was concluded that generated steam by gasification and fermentation, can improve the methane reforming in SOFC and consequently increase the overall plant efficiency. Herle et al. [11] investigate a biogas based SOFC small cogeneration system for onsite utilizations. Detailed thermodynamic modeling of fuel cell was implemented and source of biogas was landfill and agricultural waste digestion plant with fixed real composition data. Wongchanapai et al. [12] performed a thermodynamic assessment on a solid oxide fuel cell-micro gas turbine combine heat and power (SOFC-MGT CHP) system with detail thermodynamic modeling of SOFC and parametric study of important parameters was carried out at constant fuel composition (60% CH_4 and 40% CO_2). Their analysis led to a parametric-optimal design and minimum system size was achieved when fuel utilization factor in SOFC was 0.75.

Performance of a cycle can be evaluated by different terms like energy, exergy, economy of the plant and emissions. For biogas multigeneration systems different approaches have been used to study and design the system which are categorized hereafter.

1.2. Economic analysis (based on energy)

Economy of the energy systems are as important as their efficiency and environmental performance. Skorek-Osikowska et al. [13] analyzed an internal combustion engine (IC)-CHP system fueled by biogas (the source was biomass gasifier), technically and economically to evaluate the effect of system size on the heat and generated power. They concluded that the cost of fuel and green certificates are the most important factors for economic viability of the system in terms of net present value (NPV). Kang et al. [14], analyzed the economy of a CHP plant based on gas turbine using co-firing natural gas and biogas, considering a complete plant includes biogas generator. They concluded that economic of the plant is affected greatly by changes in fuel combination. Pipatmanomai, et al. [15] analyzed an IC-engine power generation scenario using pig farm wastes to produce biogas including all processes like hydrogen sulfide (H_2S) removal and evaluated payback period as function of electricity cost and governmental subsidy plans. Budzianowski and Budzianowska [16] compared pressurized and atmospheric digestion system for biogas production and biogas upgrading options and cost evaluation of different cases were taken into account. Their results showed that under current policies, pressurized digestion system and conventional CHP systems are more economically attractive. Basrawi et al. [17] investigated the optimal sizing of a cogeneration plant using economic and thermodynamic modeling. The source of biogas was a sewage treatment plant in a cold area. They analyzed three sizes of gas turbine including 30, 50 and 200 kW and concluded that NPV of 200 kW case is15% higher than 30 kW case and higher than 50 kW case.

Kang et al. [18] compared CHP and Combined Cycle based on a 5 MW biogas fueled gas turbine, economically. They considered different economic measures and heat demand patterns and selling price. Hourly thermodynamic analysis of systems was conducted with fixed fuel composition and it is concluded that CHP is generally more profitable especially at high heat demands and prices.

1.3. Off design and optimization

In addition to energy and economy analysis, off design and operation optimization of biogas-based power generation systems were carried out by some researchers. Different approaches for optimization have been proposed like parametric optimization for cycle design [19] or linear programming approach for operation strategy improvement [20]. In addition off design effects on the economy of the plant can be evaluated using methods like partial load [21] to achieve more accurate estimation of energetic and economic performance of the system.

1.4. Exergetic analysis

Exergy has been proven to be a powerful tool for evaluating the performance of energy systems. Gazda, Stanek [22] assessed a biogas fueled combined cooling, heating and power-photovoltaic panel (CCHP-PV) integrated system. Environmental assessment in terms of GHGs emission was carried out and exergetic efficiency of the plant was evaluated. They concluded that exergetic based fuel energy allocation concept is more convenient and useful than energetic method. Farhad, et al. [23] performed exergetic comparison on three different system configurations for a SOFC based micro CHP in a residential building with constant fuel composition. Hosseini et al. [24] investigated a gas turbine- organic Rankine cycle (GT-ORC) micro-power generation cycle based on the energy and exergy analyses for various biogas compositions. They carried out a parametric study on various parameters including fuel composition variations.

In some cases, exergy analysis has been used with economic evaluation of the biogas fueled plants. Performance of the systems are evaluated by exergetic performance and its' economy is evaluated by measures like Internal rate of return (IRR) and produced electricity cost [25,26]. Exergy and economy of the plant can be assessed by exergoeconomic method [27]. This method combines the exergy of flows and cost analysis and provides a value for each exergy flow. Ozdil and Tantekin [28] analyzed an onsite electricity generation for a wastewater treatment based on exergy economic analysis. A gas engine coupled with gas turbine was used for power generation and the waste heat was recovered and used in waste treatment plant. Their results showed that the cost of fuel in terms of exergy before feeding to the fuel compressor was about 4.88US/GJ.

1.5. Gas turbine fueled by biogas

Gas turbine is well known prime mover in energy systems including biogas applications. The main challenge for adopting the gas turbine for biogas is the combustion process. Depends on the biogas composition, some modifications are proposed by various researchers [29,30]. However, in general it has been shown that gas turbines can work with low LHV fuels without any change in design. Nikpey et al. [31,32] experimentally investigated a gas turbine performance fueled by biogas and provided a thermodynamic model to evaluate its off-design operation. Various biogas compositions were tested and it was concluded that a gas turbine with some improvements and tuning can operate over a range of fuel composition.

1.6. Research gap and aims of present study

Based on the best authors' knowledge, biogas-based power generation systems have been investigated in literatures widely, but in many cases:

- The composition of biogas was considered fixed.
- Exergy, energy and economy of the plant were modeled separately.
- Effects of biogas composition on both systems' exergetic and economic performance, have not been evaluated.
- Comparison between different fuel pricing methods have not been discussed.

There are some researches which cover one of the aforementioned topics but combination of all conditions was not taken into consideration to achieve a general model for biogas-based gas turbine system. In this study an exergoeconomic analysis for a biogas-based gas turbine with preheater, with respect to various fuel price and composition is presented. To add generality to the analysis, only the gas turbine has been modeled and it was assumed that biogas is provided through supply line. The effect of various biogas composition and price has been evaluated to cover all possible methods for producing the biogas. Then the price of generated power and total investment are calculated. These data are useful for evaluating the economic measures of the plant.

In summary followings are aims of this study:

- To carry exergoeconomic analysis of a biogas fueled system. This analysis provides detailed cost-exergy flows and their correlation in the cycle.
- To investigate the effect of fuel composition variations on economy and performance of the plant.
- To compare different fuel pricing methods to find out the most meaningful and reasonable approach.

1.7. Economic and performance data

Natural resources conservation services (NRCS) [33] along with national renewable energy laboratory (NREL) biogas resource characterization report [34] provided a good inside to the biogas production cost. According to mentioned references, biogas price from anaerobic digestion of livestock manure and wastes varies

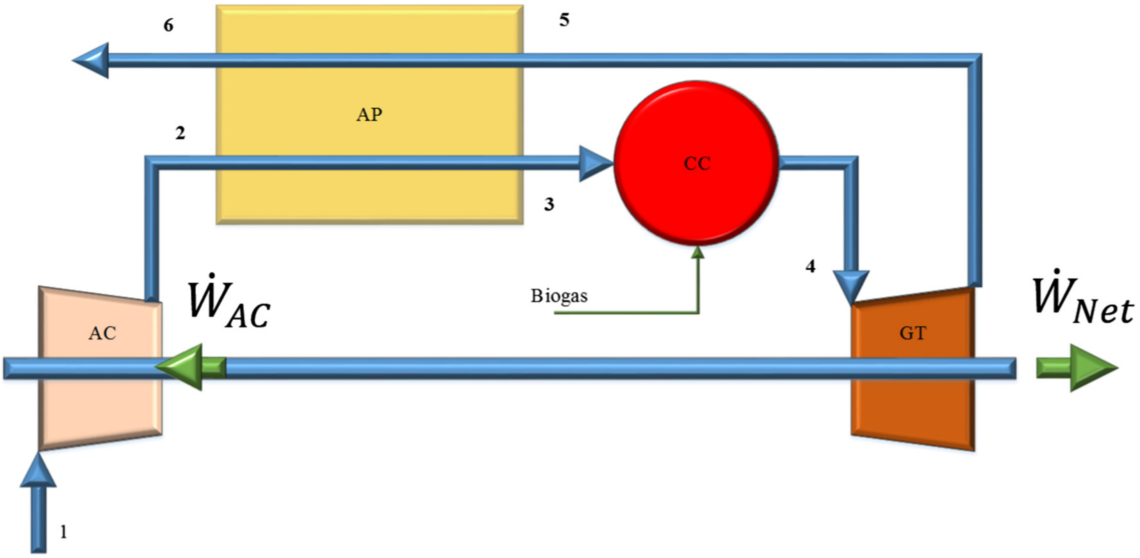


Fig. 1. Flow diagram of the gas turbine cycle with preheater.

Table 1
Thermodynamic modeling equations for the cycle.

Component	Modeling equation
Compressor (AC) Eq. (1&2)	$\dot{W}_{AC} = (h_2 - h_1)\dot{m}_a \quad (\eta_{AC} = \frac{(h_2-h_1)_{is}}{(h_2-h_1)_r}$
Gas Turbine (GT) Eq. (3&4)	$\dot{W}_{GT} = (h_4 - h_5)\dot{m}_g \quad \eta_{GT} = \frac{(h_4-h_5)_r}{(h_4-h_5)_{is}}$
Preheater (AP) Eq. (5)	$h_6 - h_5 = h_3 - h_2$
Combustor (CC) Eq. (6)	$\dot{m}_a h_3 + \dot{m}_f(LHV + h_f)\eta_{cc} = (\dot{m}_f + \dot{m}_a)h_4$
Net Power Eq. (7&8)	$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{AC} \quad \dot{m}_g = \dot{m}_a + \dot{m}_f$

Table 2
Table of inputs and accessory equations for modeling [35].

Component	Inputs and accessory equations
Compressor (AC)	$P_1 = 1\ bar \quad T_1 = 25^\circ C \quad \eta_{AC} = .83 \quad r_{AC} = \frac{P_2}{P_1} = 10$
Gas Turbine (GT)	$P_4 = .95P_3 \quad \eta_{GT} = 0.87$
Preheater (AP)	$P_5 = 1.03\ P_6$
Combustor (CC)	$\eta_{cc} = 0.98$

Table 3
Exergy balance equations for components and the system.

Component	Exergy equation	
Compressor (AC)	$\dot{E}x_1 + \dot{W}_{AC} = \dot{E}x_2 + \dot{E}xd_{AC}$	(9)
Preheater (AP)	$\dot{E}x_5 + \dot{E}x_2 = \dot{E}x_6 + \dot{E}x_3 + \dot{E}xd_{AP}$	(10)
Combustor (CC)	$\dot{E}x_3 + \dot{m}_f EX_{Fuel} = \dot{E}x_4 + \dot{E}xd_{CC}$	(11)
Gas turbine (GT)	$\dot{E}x_4 + \dot{W}_{GT} = \dot{E}x_5 + \dot{E}xd_{GT}$	(12)
Power plant (PP)	$\dot{E}xd_{total} = \dot{E}xd_{GT} + \dot{E}xd_{CC} + \dot{E}xd_{AP} + \dot{E}xd_{AC}$	(13)
	$\eta_{ex} = \frac{\dot{W}_{net}}{\dot{m}_f EX_{Fuel}}\ or\ \frac{\dot{W}_{net}}{\dot{m}_f ex_{ch}} \quad \dot{E}x_{loss} = \dot{E}x_6$	(14-16)

from 3 to 28$/GJ depends on the technologies and cases of implementation.

Methane molar or volumetric fraction in biogas is between 0.5 and 0.75 for livestock anaerobic digestion [33]. Since the methane content of biogas is low, in some cases biogas is purified to yield high concentration of methane up to 95 percent near to the same value in natural gas. The product of purification is known as bio methane and the cost of the fuel rises significantly. Economic analysis for a sample case [34] shows that the produced bio methane costs approximately11$/GJ when the cost of feeding stock was considered 6.95$/GJ. Since both composition and the price may vary widely, a cost analysis of power generation system is necessary to have an inside through the economics of the plant.

2. Methodology

Thermodynamic analysis of a gas turbine cycle at design point is carried out by methodologies presented in literatures [35]. Here a gas turbine with preheater is considered. Diagram of the plant is presented in Fig. 1.

Table 1 and Table 2 summarize equations for modeling gas turbine components. In addition, exergy analysis was considered for different components and balance the related equations are presented in Table 3. as well.

2.1. Biogas composition

Since components likes nitrogen are less than 1 percent in treated biogas, for simplicity of analysis methane and carbon dioxide have been considered as the main species of biogas.

Fuel combination has a significant effect on its chemical exergy and heating value. For gases fuel, following formula can be used to evaluate their LHV [36]:

$$LHV = \overrightarrow{LHV} \cdot \frac{\vec{Y}}{Mt} \tag{17}$$

In which $\overrightarrow{LHV}$ is the vector of LHV values for components in the mixture. For chemical exergy of the gas following formulas are used [37]. Physical exergy of the fuel is calculated based on the well-known formula of exergy. We also define the fuel to exergy ratio as follows:

$$ex_{ch} = \frac{EX_{CH} + RT_0(\vec{Y} \cdot \ln \vec{Y})}{M_t} \tag{18}$$

$$EX_{CH} = \overrightarrow{EXCH} \cdot \vec{Y} \tag{19}$$

$$M_t = \vec{M} \cdot \vec{Y} \tag{20}$$

$$\beta_0 = \frac{ex_{ch}}{LHV} \tag{21}$$

Table 4
Cost balance equations for plants components [35,38].

Component, Flow point	Cost equation Eqs. (24–29)
Point 1, air inlet	$\dot{C}_1 = 0$
Point 2	$\dot{C}_2 = \dot{C}_{W_{AC}} + \dot{Z}_{AC}$
Preheater cost balance	$\dot{C}_3 + \dot{C}_6 = \dot{C}_2 + \dot{C}_5 + \dot{Z}_{AP}$
Point 4	$\dot{C}_4 = \dot{C}_3 + \dot{C}_f + \dot{Z}_{CC}$
Turbine cost balance	$\dot{C}_5 + \dot{C}_{W_{GT}} = \dot{C}_4 + \dot{Z}_{GT}$
Plant	$\dot{C}_{tot} = \dot{C}_f + \dot{Z}_{tot}$
Accessory equations Eqs. (30–32) $\frac{\dot{C}_{W_{GT}}}{\dot{W}_{GT}} = \frac{\dot{C}_{W_{AC}}}{\dot{W}_{AC}}$ $\dot{W}_{GT} = \dot{W}_{net} + \dot{W}_{AC}$ $\frac{\dot{C}_6}{\dot{Ex}_6} = \frac{\dot{C}_5}{\dot{Ex}_5}$	

$$EX_{Fuel} = (ex_{ch} + ex_{ph})_{biogas} \tag{22}$$

$$\beta_1 = \frac{EX_{Fuel}}{LHV} \tag{23}$$

Eq. (18) is for calculating chemical exergy of a gaseous fuel mixture. EX_{CH} is the chemical exergy of composition without considering mixture activity terms and is defined in Eq. (19). EX_{CH} is the vector of chemical exergy of pure components of the mixture.

Combustion of biogas is simulated considering complete combustion assumption which is highly accurate for gas turbines. Complete explanation of biogas combustion modeling can be found in ref. [24].

2.2. Exergy economic modeling

To understand the values of different flows, exergy economic analysis is used. Here the cost rates for different flows are defined according to their exergy rates. Using cost analysis for each component as it is given in Table 4 cost value of each flow points can be evaluated.

In this formula $\dot{C}_f$ is the fuel cost and $\dot{Z}_k$ is the purchase cost of the k component in terms of ($/s or $/hr). In fact, Z is fixed cost and one may convert fixed costs to current costs using following equations:

$$\dot{Z}_k = Z_k C_{factor} \tag{33}$$

where, C_{factor} is a cost factor which converts a fixed cost value to current cost over the component's life time [39]. In this equation $i = 0.05$ is interest rate, $n = 20$ is number of years which plant is operating, $N = 8000$ is operating hours per year for the cycle excluding regular overhaul and maintenance (O&M) shutdown hours and $\varphi = 1.06$ is maintenance factor according to [38].

$$C_{factor} = \frac{i(i+1)^n}{(i+1)^n - 1} \times \frac{\varphi}{3600N} \tag{34}$$

Fuel cost is given by following formula:

$$\dot{C}_f = FP \times LHV \times \frac{\dot{m}_f}{10^6} \tag{35}$$

In this formula, FP or fuel price is given commonly in terms of ($/GJ) based on LHV of the fuel. In addition, we introduced the FP based on the total exergy of fuel:

$$\dot{C}_f = FP \times EX_{Fuel} \times \frac{\dot{m}_f}{10^6} \tag{36}$$

Difference between these two definitions is discussed thoroughly in results and discussion section.

2.3. Mass and cost factors

In this analysis, carbon dioxide mole fraction is varied from 0.05 to 0.4 and its effects on the plant economy and exergetic performance is evaluated. It is more convenient to define following parameters for presenting results of analysis:

$$\alpha_g = \frac{\dot{m}_g(X = 0.4) - \dot{m}_g(X = 0.05)}{\dot{m}_g(X = 0.05)} \times 100 \tag{37}$$

$$\alpha_0 = \frac{\dot{C}_{tot}(X = 0.4) - \dot{C}_{tot}(X = 0.05)}{\dot{C}_{tot}(X = 0.05)} \times 100 \quad C_f \text{ based on } LHV \tag{38}$$

$$\alpha_1 = \frac{\dot{C}_{tot}(X = 0.4) - \dot{C}_{tot}(X = 0.05)}{\dot{C}_{tot}(X = 0.05)} \times 100 \quad C_f \text{ based on } EX_{Fuel} \tag{39}$$

$$\alpha_Z = \frac{\dot{Z}_{tot}(X = 0.4) - \dot{Z}_{tot}(X = 0.05)}{\dot{Z}_{tot}(X = 0.05)} \times 100 \tag{40}$$

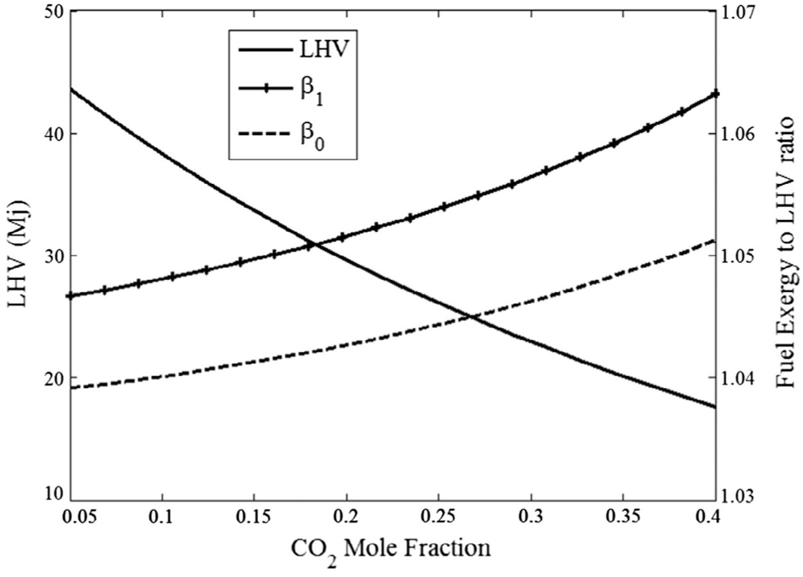


Fig. 2. Biogas LHV and exergy to LHV ratios as functions of CO_2 molar content in biogas.

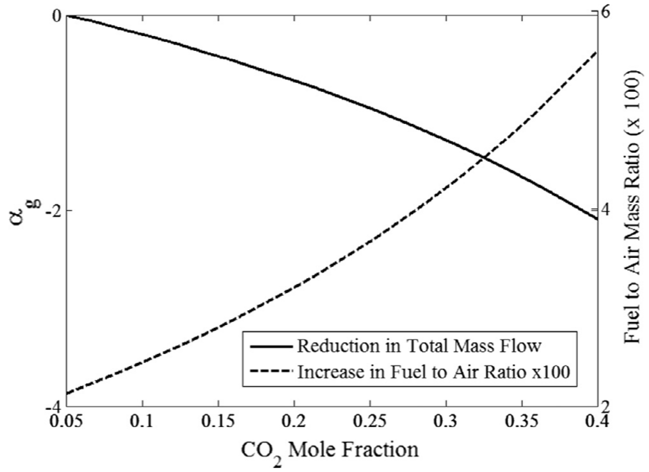


Fig. 3. Fuel to air ratio and mass factor variations. Biogas CO_2 content increases from 0.05 to 0.4.

In these formulas, variations in mass, purchase cost, and the plant total cost due to changes in fuel composition are formulated in non-dimensional parameters. To explain defined variables above, let methane percentage of 95% (X = 0.05), which is almost like the natural gas case, be considered as the base case. Then, we are going to evaluate the percentage of the changes in important parameters like turbine mass flow rate, plants' total cost rate, and equipment purchase cost (investment) while methane content is reducing to near 60%. So, we define parameters $\alpha_g, \alpha_0, \alpha_1$, and α_z to evaluate this changes in a non-dimensional manner, and in terms of% of changes. Defining this variable provides more generality to the results and the values can be easily implement for any cases as a basic estimation.

2.4. Cost of destruction and cost of exergy loss

In exergy analysis of components and cycles, two basic concepts of exergy loss and exergy destruction are taken into account. Exergy destruction is due to irreversibility's inside components or processes. Exergy loss is the exergy of flows which leaves the control volume of the system and are not products. Here, gas flow of air preheater outlet is the system exergy loss. As it was mentioned before, each exergy flow has its values or its corresponding cost flow. Here the destruction cost and exergy loss for the plant are defined as following equations:

$$\dot{C}_{Exd} = \dot{Exd}\frac{\sum \dot{C}_{in}}{\sum \dot{Ex}_{in}} \tag{41}$$

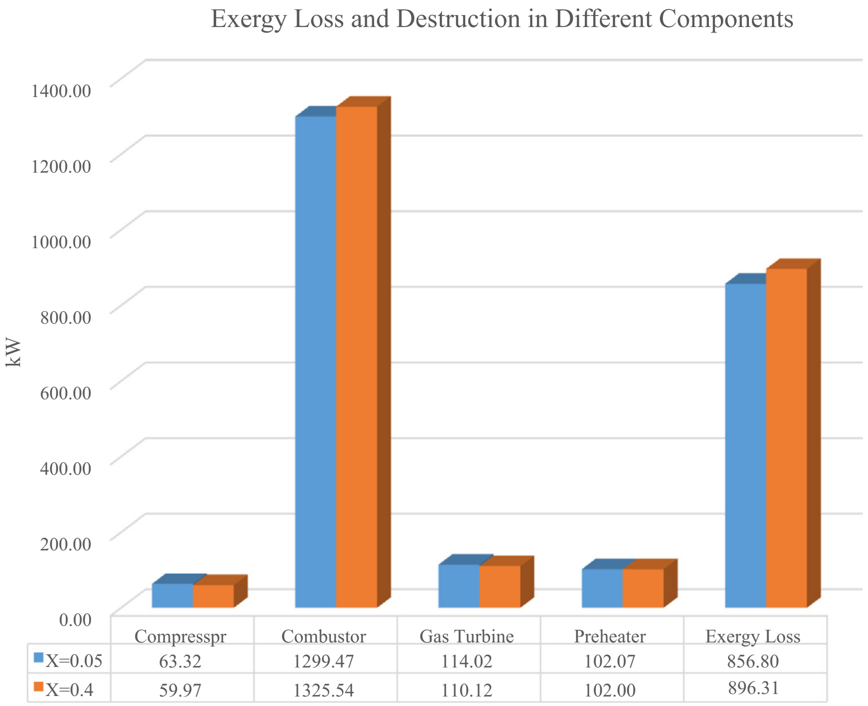
$$\dot{C}_{loss} = \dot{C}_6 \tag{42}$$

3. Results and discussion

To analysis the biogas based gas turbine cycle, the sole gas turbine biogas system was taken into account which means biogas was considered as an input source of energy or exergy to the plant with a specific price.

Biogas feeding pressure should be higher than combustor pressure because it is going to be injected into the combustion chamber and burners. This means for low LHV biogas, physical exergy of the fuel is significant and should be taken into account for both exergy and economic analysis. Usually, biogas produced on site and condition of delivering to the gas turbine depends on the biogas production technology. In general, cost of biogas is estimated in $/GJ and is calculated in terms of fuel energy (LHV). In addition to this common definition we introduce cost of biogas per total exergy of the fuel including biogas physical exergy. In Fig. 2 chemical and total exergy of the fuel are illustrated as functions of carbon dioxide concentration in the fuel. As methane concentration reduces, LHV reduces as well but chemical and total exergy ratio (exergy/LHV ratio) increase. In addition, calculations show that physical exergy is at least 1 percent of total exergy.

For modeling the gas cycle, the values in Table 2 are used. Power or work output means the net gas turbine output mechanical power and it varies from 1 to 10 MW. When fuel composition



	Compresspr	Combustor	Gas Turbine	Preheater	Exergy Loss
🟦X=0.05	63.32	1299.47	114.02	102.07	856.80
🟧X=0.4	59.97	1325.54	110.12	102.00	896.31

Fig. 4. Exergy destruction for various components. Low LHV fuel produces higher destruction in combustor and causes more losses.

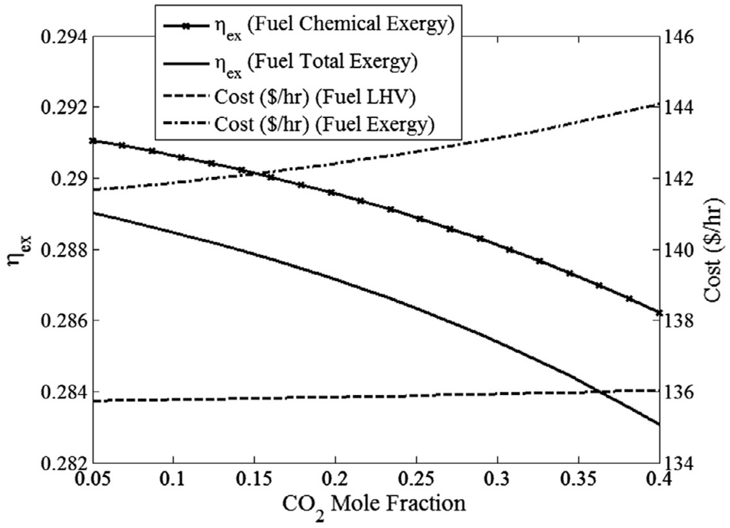


Fig. 5. η_{ex} *and* $\dot{C}_{tot}$ for the plant. This Fig. shows considering fuel physical exergy has significant impact on cost and exergetic performance.

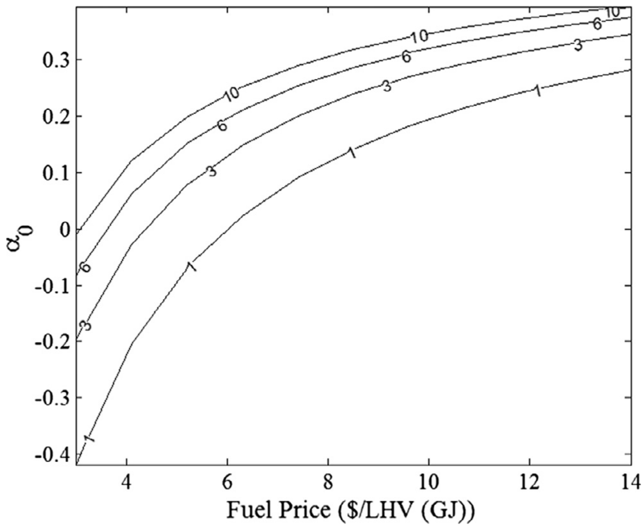


Fig. 6. Cost factor α_0 for different fuel price and net power output.

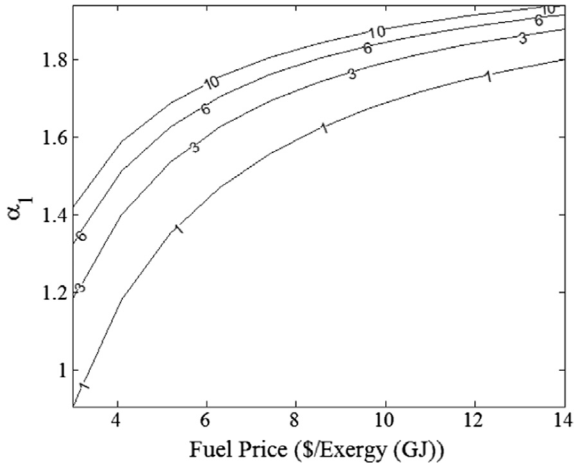


Fig. 7. Cost factor α_1 for different fuel price and net power output.

changes, at fixed turbine inlet temperature (TIT) and output power, the mass flow rate of fuel and air changes. To reach the same temperature, the mass flow rate of fuel should increase to achieve the same TIT. In this condition, total mass flow rate of gases through the gas turbine component reduces. There might be a confusing point here since power is kept constant and fuel LHV reduces why does total mass flow rate reduce too? The physical exergy of biogas is in charge for this behavior. As fuel mass flow rate increases, physical exergy of the fuel introduced more and more exergy to the cycle. This means a part of mass flow rate is compressed to the same pressure of the air without any air compressor work. So, lower air is required to be compressed for the same amount of output power. In addition, compressor work decreases which means lower value of total gas flow is enough to produce the same amount of power. Fig. 3 shows variations in total mass flow rate and fuel to air ratio while methane content in biogas reduces.

Exergetic performance for various components of the cycle is shown in Fig. 4. The amount of exergy loss as well as exergy destruction in different components of the cycle can be seen in this Fig. Results are in line with previous studies on gas turbine cycle [25,35] and exergy destruction in combustor is much higher compared to the other components. Air compressor has the least value of destruction while gas turbine component is the second largest exergy destructor in the cycle. Exergy loss of the cycle is the amount of flue gases exergy which leaves the boundary of the cycle after exchanging exergy with compressor air in the preheater. Results are for 1 MW power cycle and CO_2 concentration is varied from 0.05 (natural gas or bio methane) to 0.4 for biogas. Exergy loss and destruction for high concentration of methane are lower than fuel with 0.6 methane content because of increasing the fuel mass flow rate and exergy to LHV ratio for low concentrations of methane. In preheater, exergy of the exhaust gases increases due to air mass flow rate reduction. When air mass flow rate reduces, lower amount of gases exergy or energy is recovered because temperature of air at preheater exit (combustor inlet) is fixed.

Economic and exergetic performance of the cycle are illustrated in Fig. 5. Exergetic efficiency and total cost rate of the plant in terms of ($/hr) is presented here. In this analysis, power output is 1 MW and fuel cost is 10.7$/GJ. The studied cycle was analyzed considering two definitions of fuel cost. The first is cost of fuel which accounted for total exergy and the second is cost of fuel

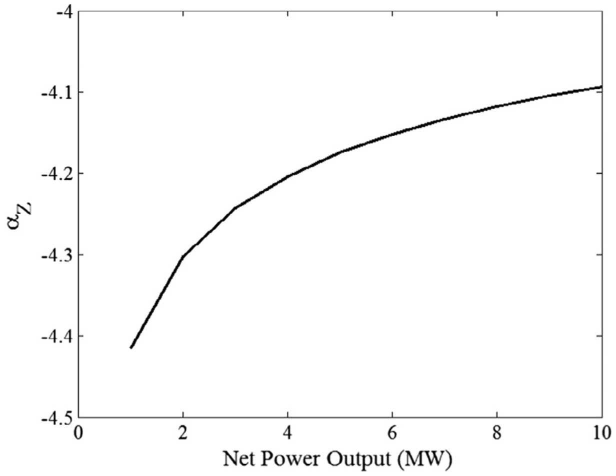


Fig. 8. Purchase cost factor.

which accounted for LHV of the biogas. In addition, total and chemical exergy of biogas was applied for performance evaluation. When methane concentration reduces, exergy efficiency decreases as well because combustion destruction and exergy loss increases when CO_2 concentration rises. Considering total fuel exergy, the exergy efficiency of the cycle is 0.3 percent lower than exergetic efficiency without considering the physical exergy of the fuel.

In the other hand, cost rate shows a different trend. When methane content falls, fuel flow rate increases, which means higher fuel cost rate. If the fuel cost for unit of fuel exergy (total) is considered the cost would be 8$/hr higher and varies more with fuel composition change.

When the cost per exergy of fuel is considered, in fact the cost of fuel compression process and fuel refining (increase energy density by methane content increment) is taken into account. This means one may pay more for higher quality fuel and higher mass flow rate of high pressurized fuel which is more accurate than fuel pricing in LHV.

In Fig. 6 and Fig. 7 cost factors α_0 and α_1 are plotted for different power output (system size) and fuel cost. In Fig. 6 fuel price is considered in terms of fuel LHV and in Fig. 7 cost of fuel is considered for total exergy of fuel. For low values of fuel α_0 has negative values which means total cost flow rate for lower content of LHV is lower. As it was mentioned before, for low LHV biogas (low rates of methane concentration), fuel flow rate increases significantly and compressor mass flow rate decrease. This means an amount of free physical exergy is introduced to the system and compressor work which makes the cost value to be reduced. For low fuel costs, this results in negative α_0 which means total cost reduces. If the total exergy of biogas is considered for pricing, α_1 is always positive. This is the more realistic and reasonable result which shows that by the fuel quality reduction for the same cost, plant cost increases. Both α_0 and α_1 augment with system size and fuel cost which is as we expected since fixed and current costs are rising as well.

Effect of methane concentration on fixed cost or purchase cost of the plant is demonstrated in Fig. 8. α_g shows how much investment cost will decrease due to methane content variations for different power outputs. The reason of this cost reduction is that mass flow rate of the system reduces especially in compressor. This results in a smaller system and reduction in components' size.

Effect of interest rate variations on the cost factors is investigated as well. Interest rate variation has no effect on the purchase cost factor. The reason is interest rate is directly correlated in CRF and to the purchase cost so it is eliminated mathematically according to definition of purchase cost factor.

Variations of α_0 and α_1 while interest rate is changing is shown in Fig. 9 and Fig. 10 respectively. While interest rate increases, total cost rate increases as well since purchase cost or investment rises. This incensement in total cost rate due to purchase cost rising, cause α_0 and α_1 to decrease. In fact, while interest rate increases, share of fixed cost (investment) in total cost increasing while current costs (fuel costs) are constant. In low fuel prices, cost factor is more sensitive to the interest rate because the share of investment cost (purchase cost) in total cost is higher than other cases. Generally, increase in system size and fuel cost reduces the sensitivity of the cost factors to the interest rates, which means in high fuel costs and system sizes, effect of fuel composition on plant total cost is small.

Cost of generated power per kWh is a unique criterion for evaluating the economic performance of the cycle. It should be noted that costs presented here may differ in various applications since cost analysis inputs and assumptions are not valid for all cases. However, the method presented here is applicable and cost values provides a reasonable estimation for biogas-gas turbine projects. Cost of generated power per kWh for six different cases is shown in Fig. 11.

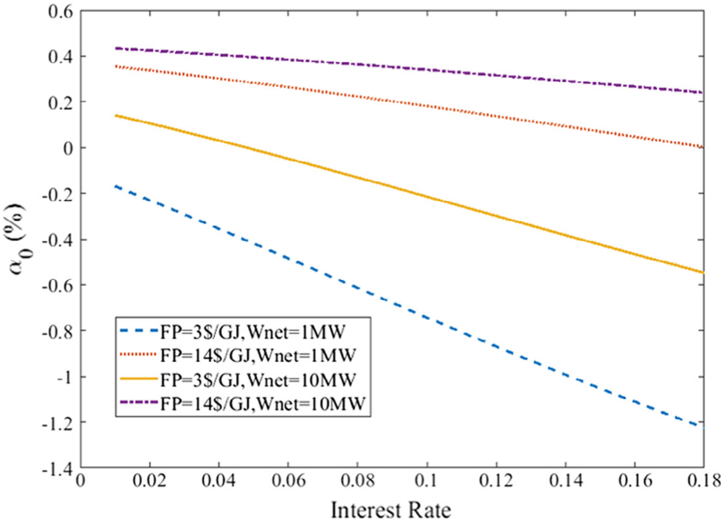


Fig. 9. Cost factor α_0 versus interest rate at different fuel price and net power output.

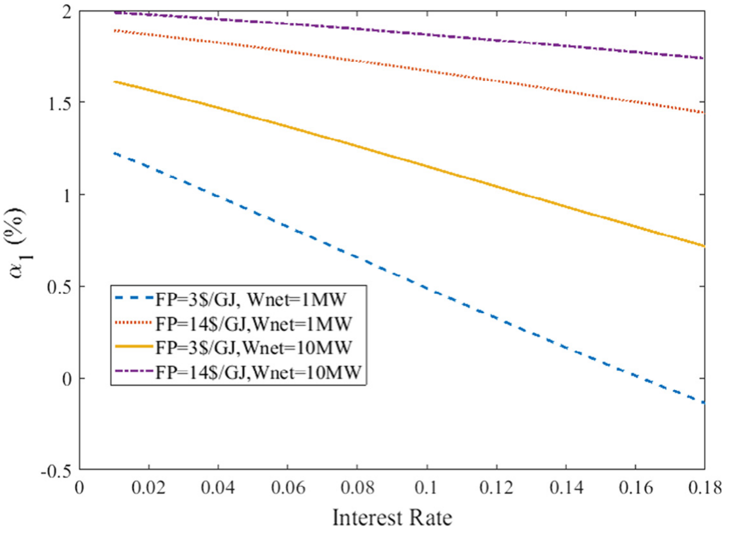


Fig. 10. Cost factor α_1 versus interest rate at different fuel price and net power output.

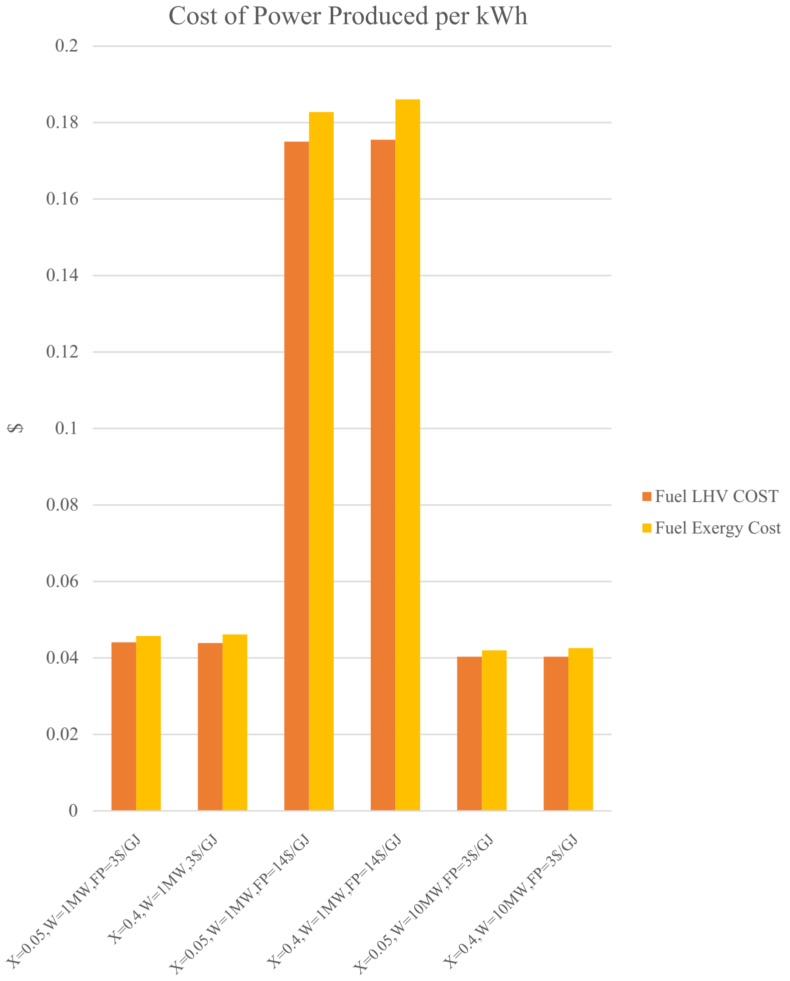


Fig. 11. Cost of power per kWh for different cases and scenarios for system size and fuel price.

For all cases biogas costing based on LHV leads to underestimation in generated power cost and the related discrepancy is more significant in higher fuel costs. Another important result is that fuel price is the most dominant cost driver in this case. Cost per unit of kWh of power reduces when system size increases. Cost of power may vary from 0.05 to 0.18$/kWh when fuel price changes from 3 to 14$/GJ.

Cost of exergy destruction and losses give more details of economic performance of the cycle and its components. As presented in Fig. 12, destruction and losses are plotted for various cases. In all

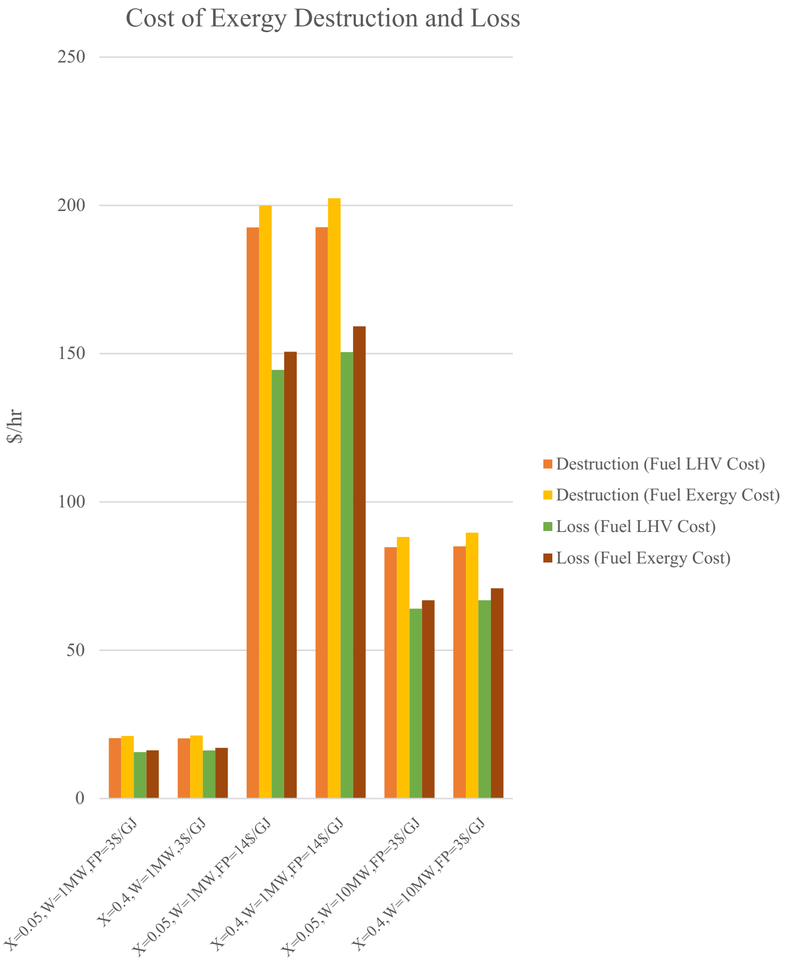


Fig. 12. Cost of exergy loss and total exergy destruction for different scenarios and system size.

cases, total destruction cost is higher than loss cost. This is due to the fact that exergy loss is lower than destruction in the cycle under analysis. In addition, cost difference between cost of destruction and energy loss is higher for higher fuel costs and system size and cost of fuel is the dominant cost driver for destruction and losses too. For both cases exergy based fuel cost leads to higher values than LHV based fuel costs.

The cycle cost performance is introduced here as an economic measure for the cycle. The cycle economic performance is defined as:

$$\eta_{eco} = 100 \times \left(1 - \frac{\dot{C}_{Loss}}{\dot{C}_{tot}}\right) \tag{43}$$

These parameter shows how much of cost which is introduced to the plant is changed into product and how much money is leaving the plant in terms of exergy loss. Since destructions are not leaving the plant, they are not taking into account in this definition. In all cases, performance factor for LHV based fuel price is higher because it introduces a free amount of exergy to the cycle (Fig. 13). For systems with same size and fuel price, economic performance of cycles with higher methane content is generally greater than cycles with lower methane content. Moreover, in the bigger system size, the economic performance is lower due to higher value of exergy losses. In fact, lower system size incurs lower value of cost of exergy loss although the cost of power generation per kWh increases.

4. Conclusion

A biogas-based gas turbine power generation system was analyzed using exergo-economic method. Effects of fuel cost, power output (system size) and fuel composition on the exergetic and economic performance of the cycle were studied. Different formula for fuel cost were used and the results were compared. In summary, findings of this study are as follows:

- Total mass flow rate of gases decreases by methane content reduction in fuel. However, fuel to air ratio rises from 2% to 6%.
- Exergy efficiency of the cycle falls more than 0.5 percent when CO_2 molar fraction in fuel rises from 0.05 to 0.4.
- Physical exergy of the fuel especially in low methane contents of biogas is significantly important and it should be taken into account.
- α_0 and α_1 measures show that how different cost definitions lead to different economic outcomes. While α_0 for low cost scenarios shows up to -0.5 percent reduction in total cost flow when CO_2 content increases from 0.05 to 0.4, α_1 parameter shows that considering total exergy cost always results in positive cost factor which means total cost flow of the plant increases by methane content reduction.
- Investment cost of the plant reduced by 4 percent when CO_2 content increases from 0.05 to 0.4.
- For 1 MW plant, cost of generated power is about 0.05$/kWh and 0.18$/kWh for fuel costs of 3$/GJ and 14$/GJ respectively.

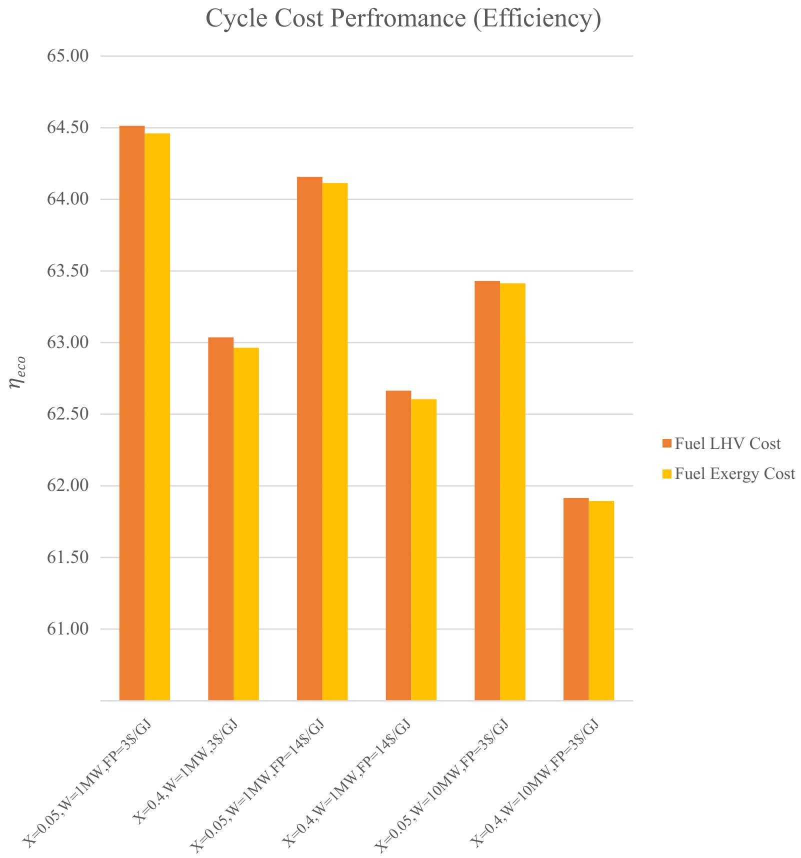


Fig. 13. η_{eco} for different cost scenarios and system size. This measure shows how much of cost flow in plant is used for power generation.

- Economic performance factor of the cycle is between 61.5 and 64.5 percent which reduces with system size, fuel cost and CO_2 content increment in biogas.

In this research fuel composition effects on both performance and economic of the plant is carried out. Total cost and performance of the plant are significantly affected by the fuel composition variations and these variations should be accounted in the planning and designing phase.

Fuel costing method is another crucial factor that should be considered. Fuel pricing in LHV term specially in low methane contents may results in lower cost and higher performance estimation. So, based on results considering fuel pricing method based on exergy is more reasonable and recommended in planning and designing phases.

Method presented here is for design and planning phase. Plant performance maybe affected significantly during operation. So, operation and off design analysis for economic and fuel composition sensitivity will be interesting.

In addition, since multigeneration is a common practice in energy systems, the same method can be implemented for biogas fueled multigeneration systems.

Acknowledgements

The authors would like to thank Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia for supporting this research activity under the Research Grant Schemes of R.J130000.7824.4F749, R.J130000.7824.4F777 and Q.J130000.2524.17H98.

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