Exergy and Exergoeconomic Assessment of Tehran'S Waste to Energy Power Plant

Amir Mohammad Behzadi, Ehsan Houshfar, Ali Habibollahzade, Ehsan Gholamian and Mehdi Ashjaee

May 24, 2018

EXERGY AND EXERGOECONOMIC ASSESSMENT OF TEHRAN'S WASTE TO ENERGY POWER PLANT

Amirmohammad Behzadi, Ehsan Houshfar, Ali Habibollahzade, Ehsan Gholamian, Mehdi Ashjaee*
School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran
*Corresponding author e-mail: *A.m.behzadi@ut.ac.ir*

ABSTRACT
Converting municipal waste into energy through the Waste-to-Energy (WtE) technology has been growing fast during the past decades. Besides the considerable reduction in the waste volume, it can generate steam and/or electricity. In the present work, energy, exergy, and exergoeconomic analysis techniques are used to investigate the performance of Tehran's 3 MW WtE plant. In the exergoeconomic analysis, the exergy cost of the stream, annual capital investment, and operating and maintenance costs are analyzed. Combination of economic principle and exergy analysis has been used to minimize the power generation costs. MSW is converted to a high enthalpy syngas via gasification to produce the required heat for steam generation in a Rankine power cycle. The effect of different inlet parameters is investigated on the target variables: net produced work, exergy efficiency, and power cost rate. Also, the exergy destruction and the exergetic efficiency of every component is calculated to assess the irreversibilities in the system. Results show that the gasifier has the highest exergy destruction. The overall exergy and energy efficiencies are 14.49% and 17.27%, respectively. Additionally, by increasing the turbine inlet pressure, the power cost rate will decrease and the net produced work and the overall system efficiency increases. It is further realized that the moisture content and gasification temperature have an indirect effect on the exergy efficiency of the gasifier.
Keywords: gasification; waste to energy; exergoeconomic; thermodynamic analysis; exergy.

1. INTRODUCTION
Current trends in the World's energy consumption caused considerable reduction in fossil fuel reserves. Consequent gradual increase in their prices beside the issues related to the emissions from their combustion and GHG effects obliged the societies to move toward renewable resources. Energy recovery from municipal solid waste (MSW) is identified by the US Environmental Protection Agency (EPA) as one of the renewable energy resources (Cheng and Hu, 2010). Since 2010 the landfill of flammable solid waste is banned in the EU countries, while the other recycling/recovery approaches are promoted, among them is the WtE technology (Ioana, 2010). Combustion, gasification, and pyrolysis are the conventional processes for thermochemical conversion of waste/biomass (Gholamian et al., 2016). Analysis of a 1 MW gasification plant indicated that the temperature of the gasifier and the excess air ratio are parameters that strongly affect the syngas composition and the gasifier efficiency (Wu et al., 2003). In a later study, Soltani *et al.* analyzed the performance of a 1 MW power plant of an externally fired gas turbine with biomass gasification and Rankine cycle (Soltani et al., 2013). In a biomass integrated gasification combined cycle plant, Bhattacharya *et al.* (Bhattacharya et al., 2011) investigated the energy and exergy analysis and the effect of main process parameters. They reported that combustion chamber has the maximum exergetic efficiency, the thermal efficiency increases with temperature ratio, and the equivalence ratio has a direct relationship with the pressure ratio.
In the present work, the system and energies are initially described in term of quantity (1st law of thermodynamics) and quality (2nd law of thermodynamics). Combination of continuity, first law, and the second law of thermodynamics are used to calculate and optimize the system performance. To the best of our knowledge, there exists no comprehensive research on energy, exergy, and exergoeconomic analysis of gasification waste-to-energy power plants. This study shed lights on the performance assessment of such systems for future deployment, with a specific attention in Iran where energy and environmental impacts are significantly in the need of improvements.

2. METHODOLOGY
Fig.1 shows a schematic diagram of the WtE plant in Tehran. The system consists of two parts: the waste gasification unit and the Rankine cycle. At the first part, Tehran's municipal solid waste (MSW) with a rather high amount of moisture is fed into the gasifier and simultaneously primary air is injected (state 6). Drying and gasification take place at the gasifier, which results in the production of a high calorific value syngas (state 8) and bottom ash. Thermodynamic and thermoeconomic analyses are performed for the system, by modeling the waste gasifier, the combustion chamber, and the Rankine cycle. We used conservation of mass, energy, and exergy with economic principles for every component using a control volume that interchanges work/heat with the surroundings. The environmental impacts are evaluated using exergy balance and therefore finding

exergy destruction for each component and the overall system. For the complete system, the energy and exergy efficiency are expressed as Eq. (1) and Eq. (2), respectively (Habibollahzade et al., 2018):

$$\eta_I = \frac{\dot{W}_{ST} - \dot{W}_P}{\dot{m}_{MSW,daf} \times LHV_{MSW,daf}} \quad (1)$$

$$\eta_{II} = \frac{\dot{W}_{ST} - \dot{W}_P}{\dot{E}_{in}} \quad (2)$$

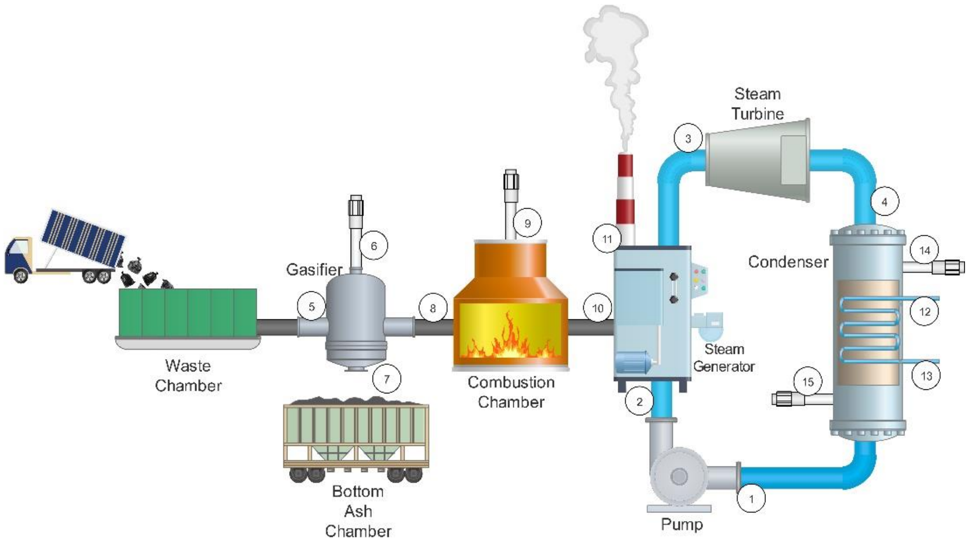

Fig. 1. Schematic of the Tehran's waste to energy plant.

The aim of exergoeconomic assessment, which is the combination of exergy analysis and economic principles, is to calculate the product cost of every component in dollar per gigajoule ($/GJ). By considering the cost rate of inlet ($\dot{C}_{in,k}$) and outlet ($\dot{C}_{out,k}$) exergy streams, the cost rate of heat transfer ($\dot{C}_{q,k}$), the cost rate of work interaction ($\dot{C}_{w,k}$), capital investment ($\dot{Z}_k^{CI}$) and operating and maintenance ($\dot{Z}_k^{OM}$), the cost balance for the kth component as a control volume can be written as:

$$\sum \dot{C}_{out,k} + \dot{C}_{w,k} = \sum \dot{C}_{in,k} + \dot{C}_{q,k} + \dot{Z}_k \quad (3)$$

3. RESULTS AND DISCUSSIONS

3.1 PARAMETRIC STUDY

A parametric study is performed to promote the plant performance. moisture content, combustion chamber temperature, turbine inlet temperature and pressure are the decision variables. The objective variables are: net output work, total cycle exergy efficiency, and turbine cost per unit of exergy (c_w). In addition, the effect of gasification temperature on the exergy efficiency of the gasifier is investigated. Fig.2(a) indicates the variation of the net output work and turbine cost, as the turbine inlet pressure changes. The increase in steam pressure causes the enthalpy to increase, so at a constant mass flow the turbine output work increases. As the turbine output work increases, the turbine cost decreases and a better cycle performance can be obtained. The increase in steam temperature, correspondingly, increases the enthalpy. Therefore, the influence of *TIT* on the net output work and the turbine cost is the same as *PIT*, as can be observed in Fig.2(b). Also, according to Fig.2(c), at higher combustion chamber temperatures, the power cost decreases, which is because of increase in the steam mass flowrate. In addition, the more moisture content at constant combustion chamber temperature results in a lower combustion product flowrate. The lower combustion product flowrate in the energy balance for steam generator causes the lower steam flowrate. Consequently, the net output work and also turbine cost will decrease. One of the most important factors on the irreversibility of a gasifier is the moisture content of the input fuel, MSW. From Fig.2(d) it can be inferred that the exergy efficiency of the gasifier increases as the moisture content increases at a constant gasification temperature. In addition, higher gasification temperatures result in higher exergy efficiencies in the gasifier and thereby less irreversibility. By increasing the gasifier temperature from 780 °C to 980 °C the exergy efficiency of the gasifier is increased about 10%, which shows a considerably positive effect from the rise of the gasification temperature.

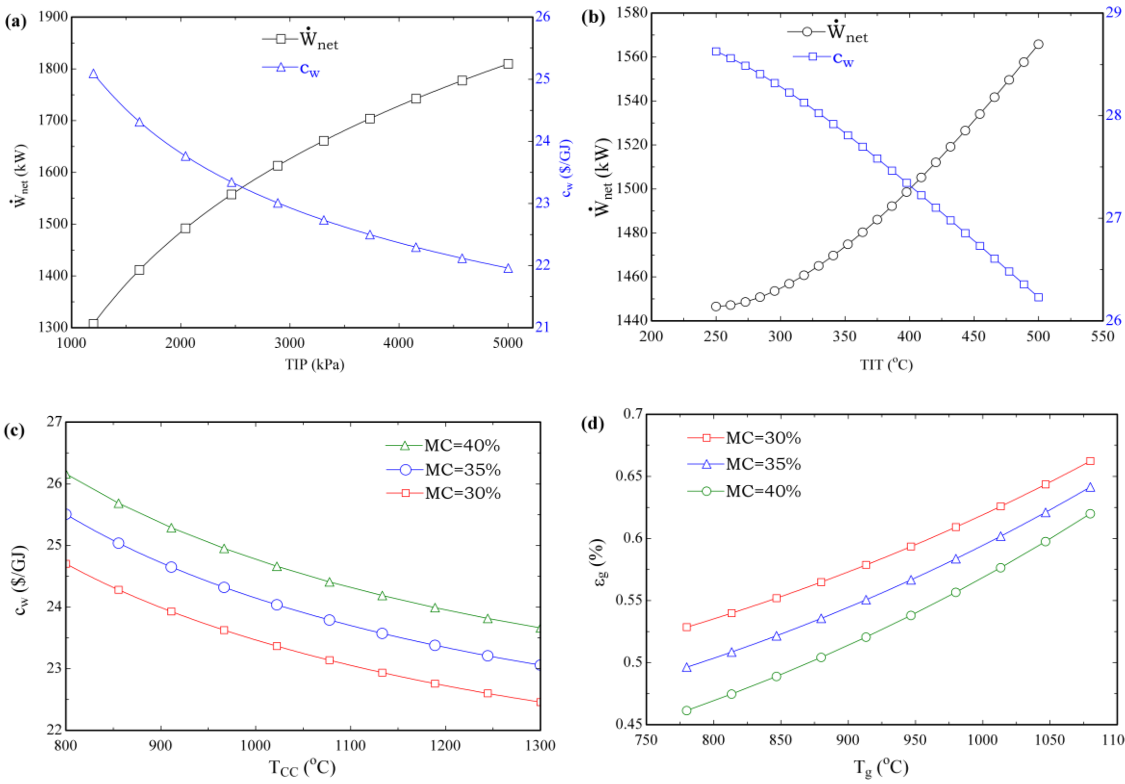

Fig. 2. a) Variation of net output work and turbine cost with turbine inlet pressure b) Variation of net output work and turbine cost with turbine inlet temperature c) Variation of turbine cost with combustion chamber temperature for three values of moisture content. d) Variation of gasifier exergetic efficiency with gasifier temperature at various moisture contents.

3.2 EXERGY AND EXERGOECONOMIC ANALYSIS

The major sources of irreversibilities are chemical reactions, temperature difference, and mixing. The results of exergy analysis indicate that the gasifier has the highest exergy destruction (3438 kW) due to the existence of all three sources in it. The second highest exergy destruction occurs in the steam generator (1980 kW) as a result of a high temperature difference between the cold and hot streams. Also, the total exergy loss (1269 kW) is comparable to the exergy destruction of the gasifier and the steam generator. The exergy destruction of the pump is nearly zero, since it increases the temperature only 0.01 °C (can be assumed as constant temperature) and moreover there is no mixing and chemical reaction. In Table 1 the exergy analysis for every component is divided into fuel/product, exergy destruction, and exergy loss. In addition, the important parameters for exergoeconomic analysis, including the cost of exergy destruction, the capital investment, operating and maintenance, and exergoeconomic factor for all components are summarized in Table 1. The lower exergoeconomic factor reveals that the cost of exergy inefficiencies is more effective than the operating and maintenance cost. For these components (with lower f), cost saving will be achieved by reducing exergy destruction by spending more money on the operating and maintenance costs, i.e., investing on equipment with better performance. On the other hand, higher exergoeconomic factors indicate that the operating and maintenance cost is more important than the cost of inefficiencies. Consequently, we must reduce the operating and maintenance cost by reducing the exergetic efficiency. For pump and steam turbine with f higher than 50%, the operating and maintenance cost plays an important role in the overall cost. The combustion chamber has an exergoeconomic factor below 2%, which is because of high exergy destruction and low operating and maintenance cost. Majority of the components have an exergoeconomic factor below 50%, which indicates that a cheap equipment has been used, so the cost of exergy destruction is high and f is low.

Table 1. Exergoeconomic parameters and factors for the proposed cycle.

Component	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	$\dot{E}_L$ (kW)	$\mathcal{E}$ (%)	$\dot{C}_D$ ($/h)	$\dot{C}_L$ ($/h)	$\dot{Z}$ ($/h)	f (%)
Gasifier	10263	6798	3438	0	66.41	24.96	0	19.6	43.99
CC	6812	5917	895.7	0	86.85	12.35	0	0.2278	1.811
Pump	4.123	4.123	0	0	100	0	0	0.65	100
ST	1828	1506	321.9	0	82.38	10.65	0	67.41	86.36
SG	4594	2615	1980	0	56.91	31.5	0	12.51	19.23
COND	791	207.4	583.6	0	26.22	19.3	0	0.2747	1.166
Stack				1269			26.15		
System	10365	1502	7219.2	1269	14.49	98.76	26.15	100.67	44.63

4. CONCLUSION

Tehran's WTE plant, which is the only MSW-based power plant in Iran, is analyzed in the present work. Two parallel cycles are investigated with overall net output work of 3 MW. The plant has been analyzed from the viewpoint of the first and the second law of thermodynamics and also exergoeconomic approach. The important conclusions are as follows:

- An increase in superheat temperature difference and combustion chamber temperature results in an increase in the net output work and thereby decreases the turbine cost.
- The moisture content is a key parameter in the change of net output work and turbine cost. As it decreases, net output work increases and the turbine cost drops.
- Gasification temperature and exergy efficiency both have a major effect on the exergy efficiency of the gasifier.
- Heat transfer on the steam generator substantially depends on the moisture content of the MSW and the steam saturation temperature. By increasing the moisture content from 30% to 40%, heat recovery on the steam generator will increase 21%.
- The gasifier has the most exergy destruction because of mixing, chemical reaction, and high temperature increase (from 25 to 980 °C).
- The effect of bottom ash in the analysis of the gasifier and overall cycle is insignificant.

REFERENCES

Bhattacharya, A., Manna, D., Paul, B., Datta, A., 2011. Biomass integrated gasi fi cation combined cycle power generation with supplementary biomass fi ring : Energy and exergy based performance analysis. Energy 36, 2599–2610. https://doi.org/10.1016/j.energy.2011.01.054

Cheng, H., Hu, Y., 2010. Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. Bioresour. Technol. 101, 3816–3824. https://doi.org/https://doi.org/10.1016/j.biortech.2010.01.040

Gholamian, E., Mahmoudi, S.M.S., Zare, V., 2016. Proposal, exergy analysis and optimization of a new biomass-based cogeneration system. Appl. Therm. Eng. 93, 223–235. https://doi.org/10.1016/j.applthermaleng.2015.09.095

Habibollahzade, A., Houshfar, E., Ashjaee, M., Behzadi, A., Gholamian, E., Mehdizadeh, H., 2018. Enhanced power generation through integrated renewable energy plants: Solar chimney and waste-to-energy. Energy Convers. Manag. 166, 48–63. https://doi.org/10.1016/j.enconman.2018.04.010

Ioana, I., 2010. Clean technology from waste management, in: Advances in Waste Management, 4th WSEAS International Conference on Waste Management, Water Pollution, Air Pollution, Indoor Climate (WWAI'10). pp. 155–171.

Soltani, S., Mahmoudi, S.M.S., Yari, M., Rosen, M. a., 2013. Thermodynamic analyses of an externally fired gas turbine combined cycle integrated with a biomass gasification plant. Energy Convers. Manag. 70, 107–115. https://doi.org/10.1016/j.enconman.2013.03.002

Wu, Z., Wu, C., Huang, H., Zheng, S., Dai, X., 2003. Test results and operation performance analysis of a 1-MW biomass gasification electric power generation system. Energy & fuels 17, 619–624.