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Comparative techno-economic-environmental assessment of biomass fueled integrated energy systems

P. Heidarnejad[1, *], H. Genceli[2], Z. Yumurtaci[2]

[1] *Department of Mechanical Engineering, Faculty of Engineering, Istanbul Gedik University, Istanbul, Turkey*

[2] *Faculty of Mechanical Engineering, Yildiz Technical University, Istanbul, Turkey*

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ABSTRACT

This paper proposes and investigates a CHP (Combined Heating and Power) system providing electricity and heating power. The considered configuration has been technically, economically and environmentally analyzed, and their performances have been compared to help designers and engineers in choosing appropriate biomass technology type for utilizing in integrated energy systems. The CHP system is studied in two modes: 1. The heat of solid waste combustion as an input 2. The heat of biogas combustion as an input. According to results, it was revealed that the exergy efficiency of the system with biogas combustion is 19% more than the system with solid waste combustion. On the other hand, the cost per exergy unit of the system with solid waste combustion was calculated to be 362.9 $/h, while the cost per exergy unit of the system with biogas combustion was estimated to be 871 $/h. Finally, the environmental assessment of the system showed that the NOx emissions of the system with solid waste combustion were 11,455 tones more than the system with biogas combustion annually. Also, the parametric study results indicated that increasing turbine inlet temperature leads to improvement in energy and exergy efficiencies of both systems by about 29% and 31%, respectively.

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1. INTRODUCTION

With increasing population growth (especially in developing countries), access to energy resources becomes more critical as the population growth has been resulted in rising of energy demand. In this situation, the combustion of fossil fuels will be responsible for the significant share of greenhouse gas emissions. On the other hand, fossil fuel resources are depleted, leading to the energy crisis. With the development of renewable energy sources such as biomass, solar, wind, geothermal, etc., as alternatives to fossil fuels and integrated to existing conventional energy systems, concerns have diminished somewhat. Meanwhile, biomass is considered as a fuel with high availability that can be utilized directly or converted to other fuels [1-6]. Some studies have been carried out in the field of biomass-driven combined heat and power systems. Dong et al. [7] carried out a review study on developing small and micro-scale biomass-fueled CHP systems. The application of ORC (Organic Rankine Cycle) and other promising technologies in these systems were compared. In another study, various biomass driven CHP technologies in the Norwegian market including MSW (Municipal Solid Waste) backpressure turbine, biogas engine, industrial backpressure turbine, district heat ORC, district heat backpressure turbine, gasification with a micro gas turbine, and other gasification technologies were studied by Kempegowda et al. [8]. Their feasibility and profitability were assessed under the Norwegian framework conditions. Energetic and economic performances of a micro-scale CHP system driven by biomass with a focus on different organic fluids was evaluated by Algieri et al. [9]. They showed that biomass driven CHP systems are an efficient alternative to achieve sustainability in the household sector. Ghasemi et al. suggested the energy of biomass combustion as a backup heat source for an integrated energy system [10]. The technical and economic feasibilities of the system were evaluated through thermodynamic and thermo-economic analyses. Zhu et al. suggested a biomass-fired CHP system including ORC (Organic Rankine Cycle). Thermodynamic and economic assessments of the cited systems were conducted, and eleven working fluids were considered to investigate the system performance [11]. In another research, Al Asfar et al. studied the performance of biomass-fired power plants

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*Corresponding author e-mail: p.heidarnejad@gmail.com

experimentally [12]. They also modelled the plant thermodynamically, economically and environmentally and validated the results with experiments. They also showed that the environmental effect of biomass combustion is disregarded due to insignificant contents of sulfur and nitrogen oxides pollutants. In some studies, hybridization of biomass combustion is carried out with other renewable energy sources; for example, Heidarnejad et al. proposed an integrated system based on biomass combustion to enhance the performance of a geothermal power plant [13]. In this research, the waste heat of biomass combustion was also recovered to provide fresh water, which is desalinated from seawater.

Moreover, limited studies have been dealt with biogas fired CHP systems. Lantz et al. studied the feasibility of different technologies of manure-based CHP systems in Sweden [14]. The results showed that the utilization of the produced heat, electricity prices, and political incentives all significantly impact the economic outcome. In contrast, the value of the digestate as fertilizer is currently having a minor impact. For example, flue gases from biogas combustion are considered heat sources for an ORC by Mudasar et al. [15]. The results demonstrated that biogas-fired ORC systems present an efficient alternative for power generation plants in rural areas. The feasibility of three different biogas utilization processes, such as biogas to methanol, biogas to bio methane and biogas to heat & electricity, were evaluated from a techno-economic viewpoint by Amaral et al. [16]. The results showed that biogas to methanol process is better than biogas to heat & electricity from the economic aspect. Zhang et al. examined a biogas CHP system for a rural area of China [17]. The utilized biogas was derived from the anaerobic digestion of cow manure which yields the primary energy saving for the CHP system for most of the year.

Tozlu et al. conducted energy and exergy analyses as well as thermo-economic modeling for an actual MSW fueled power plant located in Malatya, Turkey. According to findings, the exergy efficiency of the plant obtained to be 50.97%. Also the payback period of the system was found to be 7.7 years [18].

Holik et al. proposed a cogeneration system to recover the waste heat of two biogas-fired engines [19]. In the studied system, a part of waste heat was used as an energy source for the organic Rankine cycle and heating purposes. Also, multi-objective optimization was applied to this system considering technical and economic viewpoints to determine the system's optimum design.

In a study by Abusoglu et al., the potential of district heating and electricity production of a wastewater treatment unit that generates biogas was assessed [20]. For this evaluation, two scenarios, including district heating and electricity generation, were considered. Heat demand of 45 and 755 houses was met in the scenario I and scenario II, respectively. The electricity generation was found to increase to 1.6 MW in scenario II. Cao et al. proposed biogas fired cogeneration system for seasonal modes to cover the power, heating, and cooling demands [21]. The optimum values of the energy, exergy and leveled cost were calculated as 79.2%, 45.6%, and 21.7 $/GJ for summer and 70.7%, 37.0%, and 17.6 $/GJ for winter upon multi-objective optimization.

From the brief review presented above, it can be concluded that the comparison of two CHP systems with biogas and biomass combustion in terms of technical, economic and environmental performances have not been taken into account by researchers, which is the main novelty of this study. In this research, two CHP systems are proposed with equal amounts of products. One system consumes the energy of solid waste combustion as an input. In contrast, the other system uses the energy of biogas combustion, which is yielded as the anaerobic digestion of biomass. Both methods are investigated thermodynamically, economically and environmentally and are compared to each other. Finally, an appropriate system is suggested according to the design objectives.

2. MATERIALS AND METHODS

2.1. System Description

The typical configuration for the CHP system is depicted in Figure 1. This system is considered with two different energy inputs, separately. The first one is with solid waste combustion and utilizing the exhaust gasses of the combustion chamber, the other is with biogas combustion and utilizing the exhaust gasses of the combustion chamber in which biogas has been collected as the production of digestion of agricultural animal wastes. In the proposed CHP system, the electric power and heating are achieved through a Rankine cycle. The heat transfer between exhaust gasses and steam as the working fluid is performed through a heat recovery steam generator (HRSG). The superheated steam enters the turbine and heat exchanger to supply electric power and heating and is finally pumped into the HRSG to complete the cycle. The solid wastes are separated and prepared in the CHP with solid waste combustion before entering into the combustion chamber. On the other hand, the CHP with biogas mainly includes reactors, mixers, feeders, gas pipes and gasholders, and biogas fired combustion chambers.

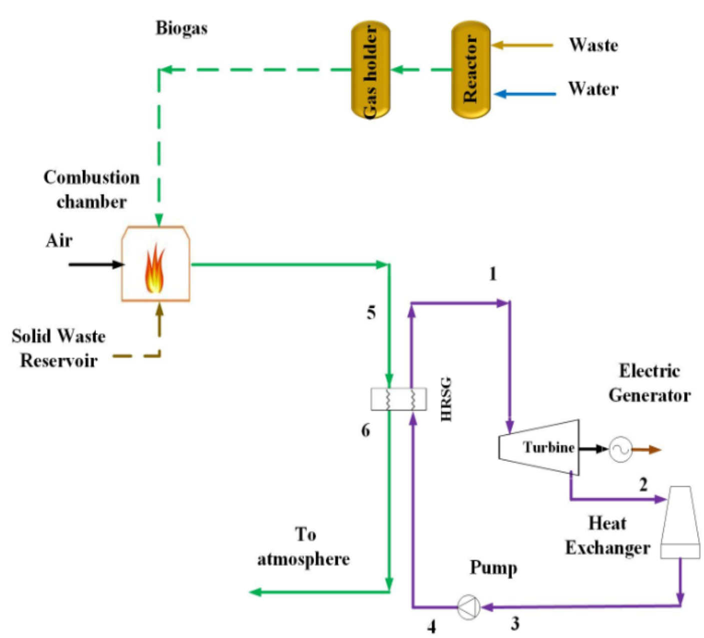

Fig. 1. The layout of the proposed CHP system.

2.2. Thermodynamic and Thermo-Economic Modeling

The thermodynamic modelling of two systems given in Figure 1 is carried out by applying each component's energy and exergy balances through Engineering Equation Solver (EES) software [22]. Besides, some simplification assumptions are considered as follows:

- Components and overall system are assumed to be under steady-state conditions.
- Potential and kinetic energy and exergies are not taken into account.
- Pinch point temperature differences in HRSG are considered to be 5 °C.
- The composition of consumed solid waste in System 1 is given in Table 1.

Table 1. Composition of the solid waste (Dry basis) [23]

Item	*Weight (%)*
Carbon	47.60
Hydrogen	6
Nitrogen	42.9
Oxygen	2.50

The energy and exergy balances on each component of the CHP system are presented as below [24, 25]:

$$\dot{Q}+\sum \dot{m}_{in}(h_{in}+\frac{1}{2}V_{in}^2+gz_{in})=\sum \dot{m}_{out}(h_{out}+\frac{1}{2}V_{out}^2+gz_{out})+\dot{W} \quad (1)$$

$$\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i+\sum \dot{m}_{in}ex_{in}=\sum \dot{m}_{out}ex_{out}+\dot{W}+\dot{E}x_D \quad (2)$$

$$ex=ex^{ph}+ex^{ch} \quad (3)$$

$$ex^{ph}=(h-h_0)-T_0(s-s_0) \quad (4)$$

$$ex^{ch}=\left[\sum_{i=1}^{n} x_i ex_i^{ch}+RT_0\sum_{i=1}^{n} x_i \ln x_i\right] \quad (5)$$

In which $\dot{m}$, $\dot{Q}$ and $\dot{W}$ refer to mass flow rate, heat transfer rate and power. Also, subscripts *i* and *e* present the inlet and outlet of the control volume, respectively. In addition, *ex* is the summation of the chemical and physical exergy of each stream. *0* express the reference environment condition. Also, ex^{ph} and ex^{ch} are physical and chemical exergy of the stream. x_i is the mole fraction of components in the mixture, the standard chemical energy of each element found in ref. [26]. Also, thermo-economic modelling as a combined tool of exergy and economical methods is performed using the below formulation [24]:

$$\sum_k (c_{out}\dot{E}x_{out})_k+c_{w,k}\dot{W}_k=c_{q,k}\dot{E}x_{q,k}+\sum_k (c_{in}\dot{E}x_{in})_k+\dot{Z}_k \quad (6)$$

$$\dot{C}_i=c_i\dot{E}x_i \quad (7)$$

$$\dot{Z}_k=\dot{Z}_k^{CI}+\dot{Z}_k^{OM}=\frac{CRF\times\delta\times PEC_k}{N\times 3600} \quad (8)$$

$$CRF=\frac{i(1+i)^n}{(1+i)^n-1} \quad (9)$$

Accordingly, c_w and c_q present the cost of exergy transfer by work and heat. Also, $\dot{Z}_k$ is the investment cost rate which can be computed based on the purchase cost of the component and system lifetime, as shown below. In this research, φ and N are assumed to be 1.06 and 7446, which denote the maintenance factor and operation hours annually [27]. Also, CRF (Capital Recovery Factor) is defined as the capital recovery factor dependent on *i* as the interest rate, and *n* is the system lifetime.

2.3. Environmental Assessment

The amount of GHGs (Greenhouse gases) emissions and pollutions emitted by the CHP system is calculated through the obtained solid waste and biogas required for each scenario. Then the emission factors provided by EPA (Environmental protection agency) [28] for solid waste combustion and by Benato et al. [29] for biogas combustion. These factors are used to achieve the amount of GHGs and pollutions emitted by each system.

3. RESULTS

In this section, results of energy, exergy and thermo-economic modelling, and environmental assessment of the CHP system with solid waste combustion and biogas combustion separately, are presented and discussed. The mathematical model developed for this system is solved through Engineering Equation Solver (EES) [22] software. The outputs of the modelling are listed in Table 2 and Table 3.

Table 2. State properties of the CHP system with solid waste combustion

State	*Mass flow rate (kg/s)*	*Temperature (°C)*	*Pressure (kPa)*	*Specific enthalpy (kJ/kg)*	*Specific entropy (kJ/kg.K)*	*Specific exergy (kJ/kg)*	*Cost per unit of exergy ($/GJ)*	*Cost rate ($/h)*
1	10	450	15000	3157	6.141	1331	0.070	3.38
2	10	198.3	1500	2725	6.303	851.3	0.070	2.16
3	10	198.3	1500	844.9	2.315	159.5	0.070	0.40
4	10	201.1	15000	863.2	2.321	176.1	0.098	0.62
5	87.58	460	100	-3544	8.141	204.6	0.014	0.95
6	87.58	250	100	-3806	7.721	67.94	0.014	0.31

Table 3. State properties of the CHP system with biogas combustion

State	*Mass flow rate (kg/s)*	*Temperature (°C)*	*Pressure (kPa)*	*Specific enthalpy (kJ/kg)*	*Specific entropy (kJ/kg.K)*	*Specific exergy (kJ/kg)*	*Cost per unit of exergy ($/GJ)*	*Cost rate ($/h)*
1	10	450	15000	3157	6.141	1331	0.068	3.29
2	10	198.3	1500	2725	6.303	851.3	0.068	2.10
3	10	198.3	1500	844.9	2.315	159.5	0.068	0.39
4	10	201.1	15000	863.2	2.321	176.1	0.096	0.61
5	107.9	460	100	425.5	7.283	165.9	0.013	0.83
6	107.9	250	100	213	6.942	55.06	0.013	0.27

Table 4. Thermodynamic and thermos-economic performances of the CHP system

Mode	$\dot{W}_{turb}$ (kW)	$\dot{Q}_{heating}$ (kW)	$\dot{m}_{SW}$ (kg/s)	$\dot{m}_{Biog}$ (kg/s)	$\dot{E}_D$ (kW)	η (%)	ε (%)	$\dot{C}_P$ $(\$/h)$
CHP system with solid waste combustion	4317	18801	2.05	-	40641	39.7	18.97	362.9
CHP system with biogas combustion	4317	18801	-	1.79	11779	39.7	37.99	871

Table 5. GHGs and pollutants from the CHP system

CHP system with solid waste combustion		
NO_x (t/y)	CO_2 (t/y)	CO (t/y)
11,822	63,633	14.99

CHP system with biogas combustion			
NO_x (t/y)	SO_2 (t/y)	CO (t/y)	VOC (t/y)
366.1	45.31	561.8	18.12

Based on the state properties of the system, thermodynamic, thermo-economic and environmental performances of the CHP system with solid waste combustion and biogas combustion separately are listed in Table 4. It is obvious from this table that, energy efficiencies of both systems are identical due to the same amounts of input energy and output energy (summation of turbine power and heating transferred by heat exchanger). On the other hand, the exergy efficiency of system two is calculated to be 19% more than the exergy efficiency of System 1. This difference is because of the difference between the amount of exergy entered into the system by solid waste combustion and biogas combustion. Also, the product cost rate of System 2 is approximately 2.4 times more than the product cost rate of System 1which is mainly because of the higher investment cost rate of system two due to the higher investment cost rate of biogas digester and plant.

The environmental assessment is performed based on calculating GHGs and pollutants from the CHP system with solid waste combustion and biogas combustion separately. This calculation is conducted based on the factors for solid waste combustion and biogas combustion, and the results are shown in Table 5. It can be seen that, from the NO_x emissions point of view, System 2 is more environment-friendly in comparison to System 1, while considering CO emissions, System 1 is more environment-friendly.

In order to have a detailed insight into the performance of System 1 and System 2, the sensitivity analysis is carried out. For this purpose, the sensitivity of the two methods' technical, economic, and environmental performance is assessed versus different decision variables. The turbine inlet temperature is a candidate as the most influencer decision parameter. The variations of energy and exergy efficiencies, product cost rate, cost per exergy unit of power, annual NO_x, CO_2 and CO emissions of Systems 1 and 2 versus the variation of turbine inlet temperature are investigated and presented through Figures 2-5. In Figure 2, the impact of turbine inlet temperature on energy and exergy efficiencies of System 1 and System 2 is demonstrated. It is shown that by increasing the turbine inlet temperature, the energy and exergy entering the turbine is increased, and the amount of power and exergy output of the system increases. The increasing energy and exergy efficiencies of System 1 and System 2 are calculated to be 29% and 31%, respectively.

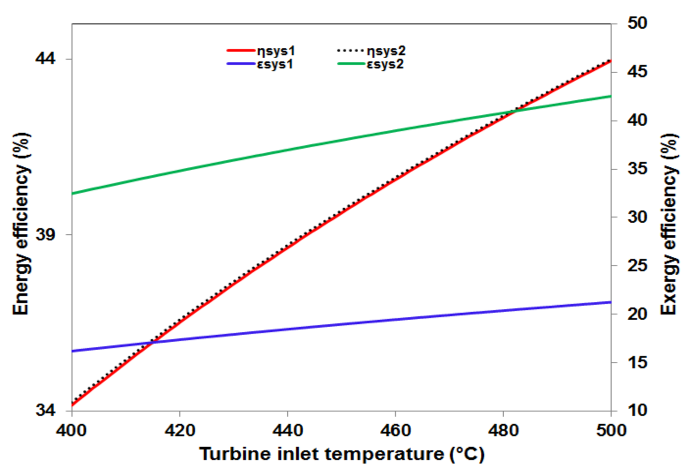

Fig. 2. The variations of energy and exergy efficiencies of System 1 and System 2 versus turbine inlet temperature.

Figure 3 indicates the impact of turbine inlet temperature on product cost rate and cost per exergy unit of power related to System 1 and System 2. It is evident that by increasing the turbine inlet temperature, the turbine's power output and investment cost increase, which leads to the decrement of price per exergy unit of power by about 6.5% for both System 1 and System 2. In the same way, the 17% increment of product cost rate of System 1 is the result of higher turbine investment cost and overall investment cost. On the other hand, in System 2, higher turbine inlet temperature means higher turbine investment cost and lower biogas plant investment cost. These contradiction phenomena contribute to decreasing and then increasing trend for product cost rate of System 2.

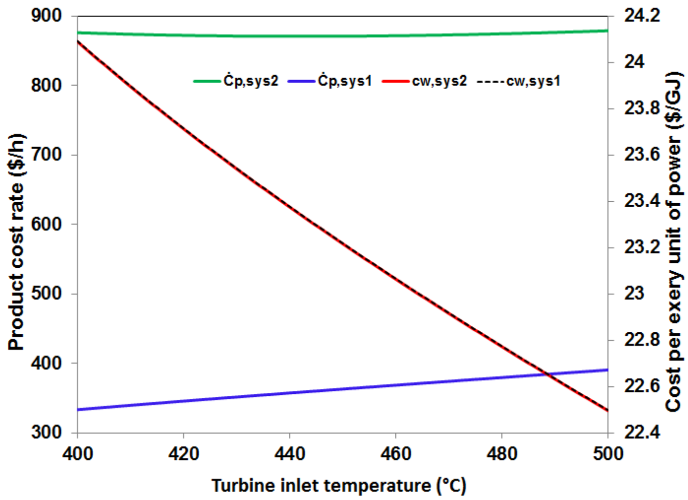

Fig. 3. The variations of product cost rate and cost per exergy unit of power are related to Systems 1 and 2 versus turbine inlet temperature.

The impact of turbine inlet temperature on annual NO_x and CO_2 emissions of System 1 is depicted in Figure 4. Higher turbine inlet temperature leads to lower turbine inlet mass flow rate and lower mass flow rate of biomass for combustion, consequently making the NO_x and CO_2 emissions of System 1 diminished by about 10%.

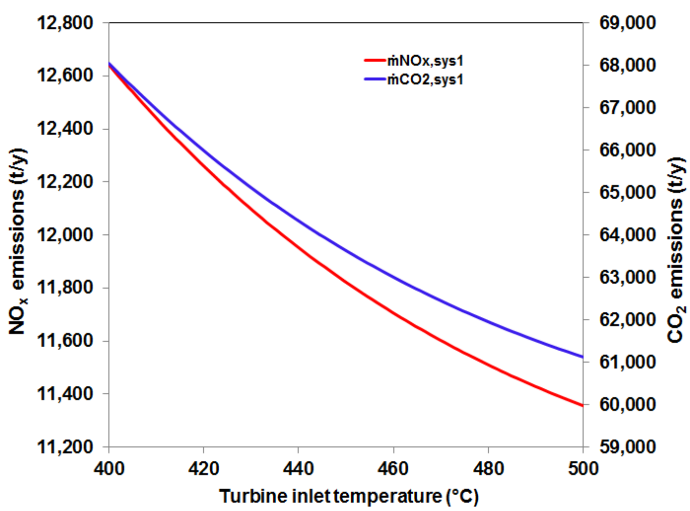

Fig. 4. The variations of annual NO_x and CO_2 emissions of System 1 versus turbine inlet temperature.

The impact of turbine inlet temperature on annual NO_x and CO emissions of System 2 is presented in Figure 5. In the same manner, higher turbine inlet temperature leads to lower turbine inlet mass flow rate and lower mass flow rate of biogas for combustion, consequently which declines the NO_x emissions for System 2 from 391.2 t/y to 351.9 t/y and the CO emissions of System 2 from 600.3 t/y to 540.1 t/y.

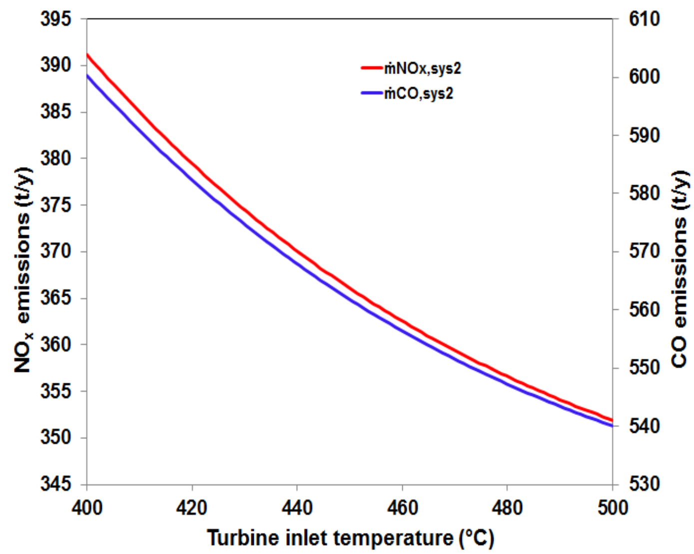

Fig. 5. The variations of annual NO_x and CO emissions of system 2 versus turbine inlet temperature.

To assure the accuracy of the developed model, the present model's obtained results related to the Rankine cycle's efficiency is compared with the results provided by Ref [30] and is presented in Figure 6. The agreement between the obtained results and data provided in the literature is quite well, proving the reliability of the developed model in this study.

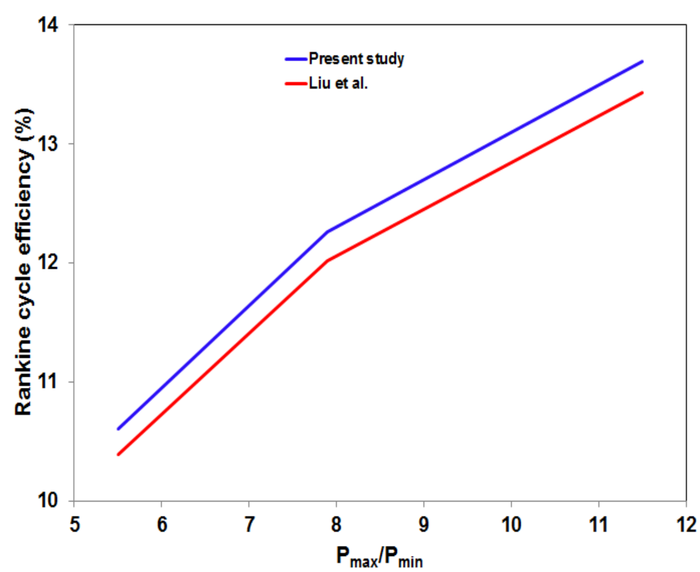

Fig. 6. Comparison of the Rankine cycle efficiency values versus pressure ratio of the turbine in the present model and model developed by Liu et al. [30].

4. CONCLUSION

In this research, a CHP system was in two modes: 1. The heat of solid combustion as the input 2. The heat of biogas combustion as the input is proposed to provide the power and heat of a rural area. To evaluate the feasibility of the proposed system, it was modelled from the thermodynamic and thermo-economic points of view, and the environmental effects were assessed. Considering the heat values of solid waste and biogas and with the purpose of providing the same amounts of products, results were obtained. Some concluding remarks can be summarized based on obtained results as below:

- Energy efficiencies of both systems are calculated to be 39.7%, while the exergy efficiencies of the system with biogas combustion ad solid waste combustion were obtained to be 37.99% and 1.97%, respectively. These efficiencies were achieved in the case of generating 4,317 kW power and 18,801 kW heating.
- From the economic viewpoint, the product cost rate of the system with solid waste combustion is calculated to be 362.9 $/h over 871 $/h for the system with biogas combustion.
- The environmental assessment of the system showed that the system with biogas combustion is more environment-friendly.
- According to a parametric study, the thermodynamic performance of both systems is more sensitive to variation of turbine inlet temperature compared to economic and environmental versions. In other words, 29% and 31% improvement is observed in energy and exergy efficiencies when turbine inlet temperature varies between 400 °C and 500 °C.

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Biographies

Parisa Heidarnejad is an assistant professor in İstanbul Gedik University. She was a postdoctoral research fellow at Yildiz Technical University, Turkey. Her specific research interest is renewable-based energy systems, environmental analysis and energy efficiency. She has co-authored one international book chapter and numerous journal articles.
E-mail: p.heidarnejad@gmail.com

Hadi Genceli is a faculty member at the Faculty of Mechanical Engineering in Yildiz Technical University, Turkey. He received his MS and PhD degrees in Mechanical engineering from Ege University in 2010 and 2014 respectively. His work focuses on renewable energy applications, heat transfer, and thermal energy storage systems. He has published more than 40 research papers in international journals and conference proceedings.
E-mail: hgenceli@yildiz.edu.tr

Zehra Yumurtaci is a Professor in the Faculty of Mechanical Engineering, Yildiz Technical University, Turkey. Her research interests cover renewable energy systems, regulation of energy markets, energy policy strategies, and energy policy. She has been involved in many collaborative projects and co-authored numerous professional journal articles. She is a member of the advisory board of WSEI (World Sustainable Energy Institute).
E-mail: zyumur@yildiz.edu.tr