Thermodynamic Analysis of Once-through Heat Recovery Steam Generator in a Combined Cycle Power Plants Fueled with Biogas

Tanti Ardiyati[1], *Edi* Supriadi[1], *Khoerul* Anwar[2], *Joko* Waluyo[1], *Rany* Puspita Dewi[3], *Hargono*[5], *Ayodya* Pradhipta Tenggara[4], *Robert* Ronal Widjaya[1], *Ary* Mauliva Hada Putri[1]

[1] Research Center for Chemistry, National Research and Innovation Agency, PUSPIPTEK, South Tangerang, 15314, Indonesia
[2] Research Center for Transportation Technology, National Research and Innovation Agency, PUSPIPTEK, South Tangerang, 15314, Indonesia
[3]Department of Mechanical Engineering, Faculty of Engineering, Tidar University, Indonesia
[4]Department of Nuclear Engineering and Engineering Physics, Faculty of Engineering, Gadjah Mada University, Indonesia
[5]Department of Chemical Engineering, Faculty of Engineering, Diponegoro University, Semarang, 50275, Indonesia

Abstract. The working principle of the combined cycle in the combined cycle power plant (CCPP) is to utilize a certain amount of waste heat in the gas turbine, which reaches temperatures of 1650°C, to generate steam in the steam turbine. Due to the high temperature of the exhaust gas in the gas turbine, a device is needed to recover this waste heat, known as a Heat Recovery Steam Generator (HRSG). Compared to conventional HRSG, a once-through heat recovery steam generator (OTHRSG) offers the advantages of faster design time (25% faster than conventional) and lower design costs because it does not require a drum which contributes to an increase in thermal efficiency. This study aims to model and simulate the CCPP system with an OTHRSG to achieve maximum thermal efficiency by using biogas from the degradation of organic waste as the input fuel for CCPP using Cycle Tempo software. The thermal efficiency of the CCPP system was achieved at 57% by applying turbine inlet temperature (TIT) of 1500°C and compression ratio of 46. These results proved that the CCPP system by using biogas as fuel could increase the thermal efficiency of a single cycle power plant.

1 Introduction

Climate change, which is initiated by the sun's heat trapped on the earth surface, causes a rise in earth's temperature, decreased rainfall, and changes in extreme weather. The utilization of fossil fuels is the main contributor to global climate change since global electricity generation is still dependent on it [1]. Coal is typically utilized as fuel in the steam power plant and makes up more than 60% of the energy mix for power plants in Indonesia [2].

Biogas is one of the renewable energies that has the potential to be utilized in place of fossil fuels in the production of electricity. Aside from that, biogas could also enhance energy security, lower greenhouse gas emissions, and provide waste management solutions. Organic Municipal Solid Waste (MSW), food waste, agricultural residues, industrial waste, sewage sludge, and cow dung are examples of the various types of organic waste material that could serve as a source for the production of biogas [3–6].

By 2022, waste generation in Indonesia will reach 35.5 million tons/year of waste where 66.67% of waste was managed and the rest was untreated. 60% cities or regencies in Indonesia use open dumping techniques as a waste management method where waste is piled up without being followed with appropriate waste processing [7]. As the waste generates rapidly, the capacity of landfills in Indonesia decreases overtime so that several landfills are already overcapacity and likely to close. To overcome the waste problem, the local government expands the landfill area or opens up empty land to accommodate the waste. Such conditions will happen repeatedly if there is no further action to overcome the landfill waste problem. Moreover, disease, air pollution, water pollution and the threat of fire from generated methane gas can threaten local residents.

Waste to Energy Power Plant (PLTSa) comes up as a solution to overcome the waste problem in Indonesia by utilizing thermal incineration methods into electrical energy. The majority of PLTSa are found on Java Island. Some examples include the PLTSa Merah Putih at the TPST Bantar Gebang in Bekasi, PLTSa Benowo at TPA Benowo in Surabaya, and the PLTSa Jatibarang at TPA Jatibarang in Semarang [8].

In the PLTSa, the heat generated from the incineration process is used to convert the water in the steam boiler into superheated steam. The superheated steam passes through a high-pressure turbine to generate power in the generator, which can then produce electricity. The flue gasses coming out from the incineration process are treated to prevent the formation of harmful pollutant gasses and are further filtered in a bag house filter to meet emission quality standards. The residue of fly ash and bottom ash from the remaining incineration waste can be utilized as construction materials (bricks, paving blocks, etc.).

The burning of waste by incineration method has been proven to produce hazardous gasses such as dioxins, polychlorinated dibenzofurans (PCDFs) and poly-brominated compounds [9–11]. Although dioxin and furan may be eliminated during high temperatures incineration process, they have the potential to regenerate in post-combustion process [11,12]. Hence, the flue gas treatment is a relatively costly operation which causes the initial investment cost relatively high [13].

Combined Cycle Power Plant (CCPP) technology can be offered as an alternative to environmentally friendly power plants using biogas as its fuel. CCPP can increase the efficiency of a gas turbine with a simple cycle from about 20% to 64% [14]. In order to achieve such high efficiency, system losses must be kept to a minimum by providing the gas turbine's temperature inlet as high as possible and the gas outlet temperature as low as possible [15]. The CCPP combines two cycles, the Brayton cycle that works at very high temperatures (up to 1650°C) and the Rankine cycle which works at low temperatures (up to 650°C). The wasted heat from the gas turbine is used to heat the working fluid at the HRSG, which then produces superheated steam that is then used to move the blade of the steam turbines to generate electricity.

In this research, the authors intend to design a CCPP equipped with an OTHRSG which has relatively high thermal efficiency [16,17]. The potential for methane gas produced from the degradation of organic waste is also of concern to authors. In this research, a thermodynamics study will be carried out on the design of CCPP using a once-through type HRSG, specifically by utilizing the potential of biogas from organic waste in landfills as fuel in the gas turbine system. Thermodynamic analysis is the main focus in this research study, so that optimization conditions and maximum thermal efficiency can be obtained from the power generation system.

2 Methodology

The data on the volume and composition of waste were obtained from Piyungan Landfill (TPA Piyungan) in Yogyakarta. The data for potency of biogas generated from TPA Piyungan was gathered from its landfill waste data. The potential values of biogas are determined in three conditions, among others optimistic, pessimistic and average conditions.

Several criterias were used to determine the design conditions for the power plant, including: the highest possible combined cycle efficiency; the maximum turbine inlet temperature (TIT) entering the gas turbine is 1,500°C; optimized compression ratio within the Brayton cycle are in the range of 30 to 46 [20]; maximized net thermal power of the CCPP.

In the gas turbine system, atmospheric air and biogas are optimized in the compressor, which has an efficiency of 88%, temperature of 25°C and pressure of 1 atm. Those working fluids were then flown to the combustion chamber which was assumed to be in a steady-flow and adiabatic condition, meaning no heat loss ($Q = 0$). The combustion gases were then expanded into the gas turbine, which has an efficiency of 93%. The maximum operating temperature for the TIT was 1500°C. From the turbine expansion, flue gas was generated at a predetermined pressure of 1.5 bar, so that it can exit through the OTHRSG toward the stack.

The wasted heat from the gas turbine is then expanded into the OTHRSG. The OTHRSG used in this study has a once-through type with three pressures, i.e high, intermediate and low pressures. OTHRSG efficiency is assumed to be 90%, while high, intermediate and low pressures are 90 bar, 20 bar and 5 bar, respectively. Preheaters are assumed to have a pressure of 2 bars. The analysis performed on the OTHRSG system was focused on the flue gas exiting the gas turbine with maximum TIT of 1500°C, with the compression ratio varying between 30 to 46.

In this research, the steam turbine system consisted of high-pressure turbine, intermediate-pressure turbine, and low-pressure turbine, which have efficiency of 90% each and pressures that were adjusted to the condition of OTHRSG. Thermodynamic simulation of the CCPP and three pressure OTHRSG was performed using Cycle Tempo software. Cycle Tempo software is able to design, analyze, and optimize the thermodynamics of the CCPP system.

2.1 Gas Turbine Cycle (Brayton Cycle)

Gas turbine system operates based on the Brayton cycle which consists of three main components: compressor, combustion chamber, and turbine. On the gas turbine, atmospheric air and biogas are flowing into the compressor, which serves to raise the pressure of the air and biogas, so that the temperature will increase as well. Subsequently, the pressurized and high-temperature air and biogas enter the combustion chamber. The combustion process takes place at a constant pressure, so the combustion chamber is solely used to raise the temperature of the respective working fluid. The high-temperature gas produced from the combustion process is then expanded through the blades of a gas turbine to rotate the generator.

Compression ratio is one of the most influential parameters of the thermal efficiency value of the Brayton cycle [18]. The pressure of the atmospheric mixture with the biogas fuel in the combustion chamber depends on the optimized compression ratio. In this study, the compression ratios will be varied to the maximum thermal efficiency of the Brayton cycle, taking into account the turbine material strength temperature.

Thermal efficiency Brayton cycle in gas turbine can be calculated using following equation:

$$\eta_{SB} = \frac{\dot{W}_{net\ (Brayton)}}{\dot{Q}_{flame}} \times 100 \tag{1}$$

2.2 Once Through Heat Recovery Steam Generator

In a combined cycle system, Heat Recovery Steam Generator (HRSG) is one of the important components. HRSG functions as a heat exchanger, consisting of several parts, including a preheater, economizer, evaporator, and superheater. These equipements are used in the steam generation process [18].

The HRSG used in this research is a multi-pressure system with a once-through type, involving three pressure levels. The multi-pressure system has been proven can enhance the energy performance of power generation systems. In the once-through type, the feedwater entering the HRSG is heated, vaporized, and further heated in a single pass. This type of HRSG does not require a steam drum to separate saturated steam from boiling water, and there is no water recirculation, making the system simpler and the process faster [19].

2.3 Steam Cycle (Rankine Cycle)

The steam turbine used in this study has three pressure levels, as found in the OTHRSG. These three pressure-level turbines are high-pressure, intermediate-pressure, and low-pressure turbines. The optimum operating conditions for the turbines include temperature and pressure, determined based on the assumption and reference to the requirement that the inlet temperature of the steam turbine must be lower than the inlet temperature of the gas turbine.

The analysis of the conditions in the steam turbine is divided into two categories: conditions before expansion and conditions after expansion. The working fluid conditions in the steam turbine before expansion are a continuation of the conditions of the fluid exiting the OTHRSG. The pressure and temperature conditions in the steam turbine adapt to the pressure and temperature conditions in the OTHRSG. Similarly, the mass flow rate and specific heat capacity of the working fluid at each steam turbine pressure level are adjusted to match the conditions present in the HRSG.

The thermal efficiency of the Rankine cycle can be expressed as follows:

$$\eta_{SR} = \frac{\dot{W}_{net(Rankine)}}{\dot{Q}_{in,OTHRSG}} \times 100 \tag{2}$$

Therefore, the thermal efficiency of the combined cycle is the sum of the net thermal power of the Brayton cycle and the Rankine cycle divided by the heat required for the combustion process of air and biogas fuel in the combustion chamber. The thermal efficiency of the combined cycle can be expressed as follows:

$$\eta_{CC} = \frac{\dot{W}_{net(Brayton)} + \dot{W}_{net(Rankine)}}{\dot{Q}_{flame}} \times 100 \tag{3}$$

3 Result and Discussion

Waste processing is necessary to address the current waste problems in Indonesia. One of the ways to do this is by harnessing methane gas generated from organic waste in landfills to produce biogas, which can then be converted into electricity through a power plant. Combined cycle was used as a power plant since it can increase the thermal efficiency of the simple Brayton cycle up to 64% by utilizing the wasted heat from the gas turbine to generate steam in the steam turbine [14].

In this research, the waste components in the landfill that can be processed into biogas include organic waste and food waste. In TPA Piyungan, the percentage of waste that can be degraded into biogas by 2022 was 64.1% of the total waste composition from total 110,642 ton/ year waste in 2022. From the data, we can calculate the potential molar flow rate of biogas in the pessimistic, optimistic and average conditions are 0.008 kmol/s, 0.026 kmol/s and 0.016 kmol/s, respectively.

The inlet gas temperature to be expanded into the gas turbine was set to the maximum of 1,500°C since the material strength of the turbine can operate up to a maximum temperature of 1,500°C for G and H class type gas turbines [14]. From the research of the effect of compression ratio on thermal efficiency of the Brayton and Rankine cycles [20], to get the maximum thermal efficiency of the combination cycle as of 57 %, then the turbine inlet temperature was 1,500°C and the compression ratio was 46. Maximum net thermal power is one of the design criteria on the CCPP. The maximum net thermal power of 7.50 MW with a compression ratio of 46 is achieved in optimistic conditions [20]. Therefore, the molar flow rate of biogas for the operational design of the CCPP used optimistic conditions at 0.026 kmol/s. Table 1 below shows several parameters that affect the energy calculation on the Brayton cycle and gas turbine's operating condition. These operating parameters were optimized to obtain the highest efficiency of the system. In this design, with a compression ratio of 46 and an inlet gas turbine temperature of 1500°C resulted in the thermal efficiency of the Brayton cycle achieved at 42.02%.

Table 1. Brayton cycle operating conditions and energy calculation

Parameter	Units	Operating condition
Compressor		
Biogas fuel molar flow rate, $\dot{m}_{bb}$	kmol/s	0.026
Air molar flow rate, $\dot{m}_{u}$	kmol/s	0.4
Air and biogas compressor efficiency, η_{K}	%	88
Compression ratio, r_{p}		46
Air compressor power, $\dot{W}_{Ku}$	MW	7.4
Biogas compressor power, $\dot{W}_{Kbb}$	MW	0.5
Total compressor power, $\dot{W}_{Ktot}$	MW	7.9
Combustion chamber		
Combustion chamber pressure, P_{RB}	bar	46
Percentage of excess air required, *excess air*	%	139.0
Calorific value of biogas fuel, LHV	kJ/kg	20630.5
Combustion heat rate, $\dot{Q}_{flame}$	MW	13.2
Mass flow rate of biogas fuel, $\dot{m}_{bb}$	kg/s	0.64
Air mass flow rate, $\dot{m}_{u}$	kg/s	11.04
Mass flow rate of gas product, $\dot{m}_{p}$	kg/s	11.7
Gas turbine		
Gas turbine efficiency, η_{TG}	%	93
Gas turbine actual power, $\dot{W}_{(TG)}$	MW	13.5
Net thermal power of Brayton cycle, $\dot{W}_{net(SB)}$	MW	5.5
Thermal efficiency of Brayton cycle, η_{B}	%	42.02

The results of the Brayton cycle energy calculations will affect the energy calculations in the Rankine cycle. The value of compression ratio and the mass flow rate of biogas will affect the value of the steam mass flow on the OTHRSG. Further changes in the OTHRSG steam mass flow rate will influence the vaue of the temperature of steam turbine inlet and the thermal efficiency of the rankine cycle. Rankine cycle operating conditions can be seen in the Table 2 below.

Table 2. Rankine cycle operating conditions and energy calculation

Parameter	Units	Value
Once-Through Recovery Steam Generator		
Gas mass flow rate, $\dot{m}_a$	kg/s	11,7
Efficiency OTHRSG, η_{HRSG}	%	90
Total heat transfer rate, $\dot{Q}_{in}$	kW	6493,5
Fluid mass flow rate for high pressure, $\dot{m}_f$	kg/s	2.05
Fluid mass flow rate for intermediate pressure, $\dot{m}_f$	kg/s	0.09
Fluid mass flow rate for low pressure, $\dot{m}_f$	kg/s	0.01
Pump		
High pressure pump power, $\dot{W}_{p.HP}$	kW	22.6
High pressure pump power, $\dot{W}_{p.IP}$	kW	3.9
High pressure pump power, $\dot{W}_{p.LP}$	kW	0.7
Condenser pump power, $\dot{W}_{kondenser}$	kW	0.4
Total pump power, $\dot{W}_{p(tot)}$	kW	27.6
Condenser		
Condenser pressure, $P_{kondenser}$	bar	0.2
Steam Turbine		
Turbine efficiency, η_{TU}	%	92
High pressure turbine power, $\dot{W}_{TU\ HP}$	kW	569.8
High pressure turbine power, $\dot{W}_{TU\ IP}$	kW	955.2
High pressure turbine power, $\dot{W}_{TU\ LP}$	kW	472.0
Total turbine power, $\dot{W}_{TU(tot)}$	kW	1997.0
Rankine cycle net thermal power, $\dot{W}_{(SR)}$	MW	1.97
Rankine cycle thermal efficiency, η_R	%	30.3
Combined cycle net thermal power, $\dot{W}_{net(CC)}$	MW	7.5
Combined cycle thermal efficiency, η_{CC}	%	57.0

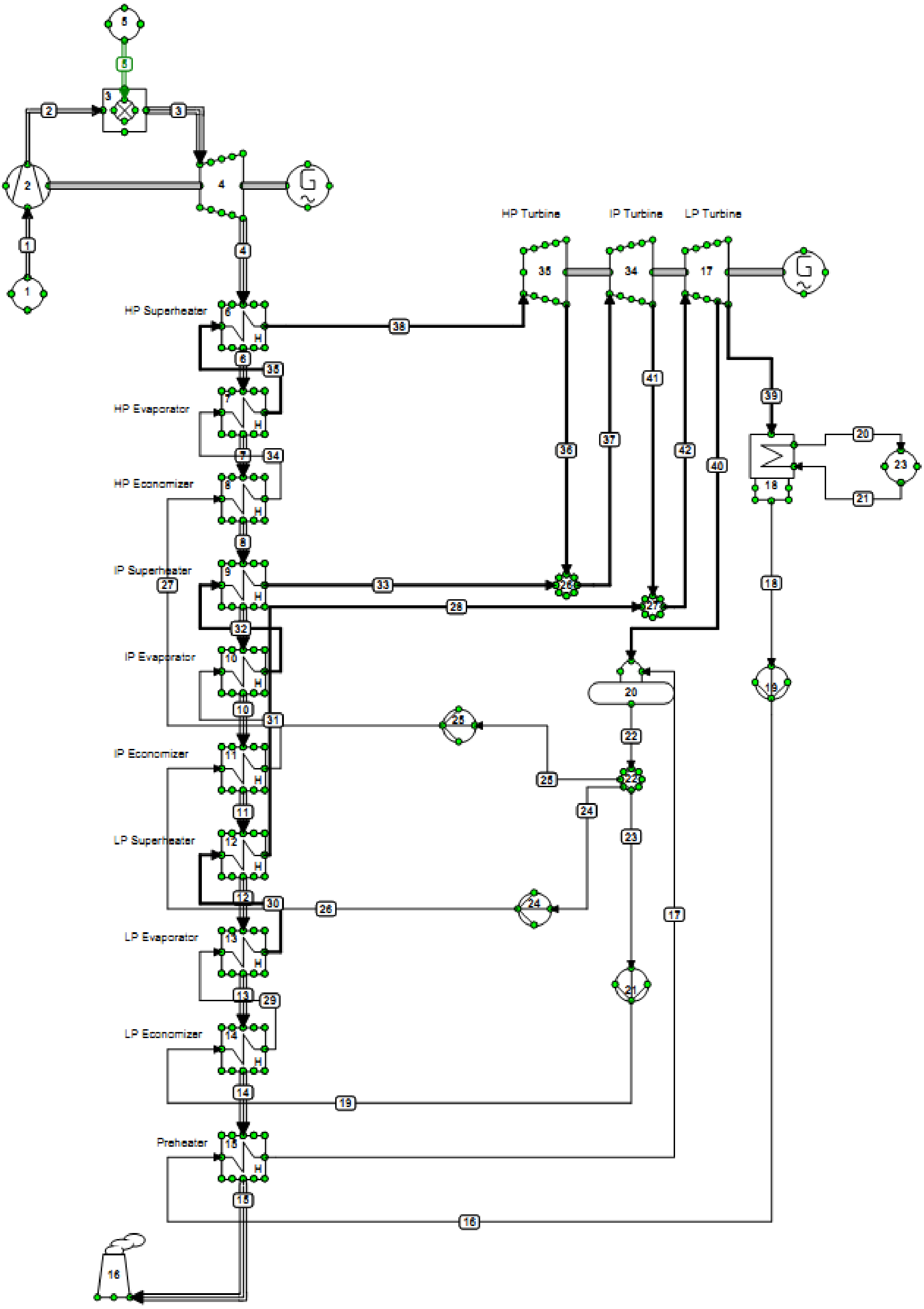

Fig. 1. Model of CCPP and OTHRSG İn Cycle Tempo Software

 https://doi.org/10.1051/e3sconf/202450304008

Table 3. CCPP thermodynamics of calculation and cycle tempo results

Parameter	Calculation Result			Cycle Tempo result		
	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)
a. Compressor						
Air inlet	1	25		1	25	-88.75
Biogas inlet	1	25		1	25	-88.75
b. Combustion chamber						
Air inlet	46	649.8		46	654.03	580.37
Biogas inlet	46	621		46	600	3222.25
c. Gas turbine						
Turbine inlet	46	1500		46	1500	-1103.18
Turbine outlet	1.5	606		1.5	631.26	-2302.78
d. Once-Through Recovery Steam Generator						
4.1 High Pressure						
a. Superheater						
Fluid inlet	90	308.0		90	460	3284.38
Fluid outlet	90	576.9	2848.22	90	631.25	3710.01
Gas inlet	1.5	606.0		1.5	631.26	-2302.78
Gas outlet	1.5	545.7		1.5	500	-2468.45
b. Evaporator						
Fluid inlet				90	260	1134.23
Fluid outlet				90	460	3284.38
Gas inlet	1.5	545.7		1.5	500	-2468.45
Gas outlet	1.5	349.6		1.5	300	-2710.32
c. Economizer						
Fluid inlet	90	208.0		90	101	430.00
Fluid outlet	90	308.0		90	260	1134.23
Gas inlet	1.5	349.6		1.5	300	-2710.32
Gas outlet	1.5	259.8		1.5	141	-2894.03
4.2. Intermediate Pressure						
Superheater						
Fluid inlet	20	208.0		20	210	897.76
Fluid outlet	20	211.9	2713.28	20	141	594.56
Gas inlet	1.5	259.8		1.5	141	-2894.03
Gas outlet	1.5	259.8		1.5	250	-2768.85
Evaporator						
Fluid inlet				20	210	897.76
Fluid outlet				20	210	897.76
Gas inlet	1.5	259.8		1.5	250	-2768.85
Gas outlet	1.5	246.7		1.5	250	-2768.85
Economizer						
Fluid inlet	20	144.8		20	100.21	421.43
Fluid outlet	20	208.0		20	210	897.76
Gas inlet	1.5	246.7		1.5	250	-2768.85
Gas outlet	1.5	186.9		1.5	140.21	-2894.92

Parameter	Calculation Result			Cycle Tempo result		
	Pressure (bar)	**Tempe rature (°C)**	**Enthalpy (kJ/kg)**	**Pressure (bar)**	**Temp eratur e (°C)**	**Enthalpy (kJ/kg)**
4.2. Low Pressure						
Superheater						
Fluid inlet	5	144.8		5	160	2767.38
Fluid outlet	5	146.9	2826.24	5	140.13	589.86
Gas inlet	1	186.9		1	140.13	-2894.92
Gas outlet	1	186.9		1	200	-2826.60
Evaporator						
Fluid inlet				5	160	2767.38
Fluid outlet				5	160	2767.38
Gas inlet	1	186.9		1	200	-2826.60
Gas outlet	1	185.2		1	200	-2826.60
Economizer						
Fluid inlet	5	114.0		5	100.05	419.59
Fluid outlet	5	144.8		5	160	2767.38
Gas inlet	1	185.2		1	200	-2826.60
Gas outlet	1	155.7		1	140.05	-2895.02
4.3. Preheater						
Fluid inlet	2	59.8		2	60.07	251.62
Fluid outlet	2	114.0		2	70.88	296.86
Gas inlet	1	155.7		1	140.05	-2895.02
Gas outlet	1	116.4		1	100	-2940.27

In this research, a comparation and validation of the simulation results with the calculation were performed. From the table, we can see that the values are mostly different due to the assumptions used and values applied in the Cycle Tempo software. However the values are not much different, it may be disregarded.

From the calculations and the cycle tempo simulation results, we obtained the design of a CCPP that has a high thermal efficiency at 57%. The thermal efficiency for brayton cycle, and rankine cycle were achieved at 42.2% and 30.3%, respectively. Such high thermal efficiency was influenced by the use of OTHRSG which utilizes the heat wasted from gas turbines to generate steam on steam turbine with once-through technology, thereby improving the entire performance of power plant systems.

On the OTHRSG system, the flue gas from the turbine gas enters the high pressure superheater at a temperature of 606°C and 631.26°C for the calculation and cycle tempo results repectively. Furthermore, in this system, the flue gas then left the preheater at a temperature of 116.4 °C and 100°C for the calculation and cycle tempo results repectively.

4 Conclusion

On this power plant design, the determination of the operating point conditions is based on thermal efficiency and gas turbine inlet temperature. Designing the CCPP with a compression ratio of 46 results in a combined cycle thermal efficiency of 57 % with a turbine inlet temperature of 1500°C. Under these conditions, the thermal efficiency of the

Brayton cycle achieved is 42.02 %, while the thermal efficiency of the Rankine cycle achieved is 30.3 %. The maximum net thermal power generated by the CCPP was 7.5 MW. The flue gas from the expansion of the gas turbine, which would heat the working fluid in the OTHRSG, entered the high-pressure superheater at a temperature of 606°C and 631.26°C for the calculation and cycle tempo results repectively. The gas then left the preheater at a temperature of 116.4 °C and 100°C for the calculation and cycle tempo results repectively. The thermal efficiency for brayton cycle, rankine cycle and combined cycle were achieved at 42.2%, 30.3%, and 57%, respectively. These results proved that the ultilization of CCPP for electricity generation increased the thermal efficiency of the brayton cycle. The use of biogas as a fuel turned out to be able to make CCPP have a high thermal efficiency, but further research needs to be performed to maximize the thermal effeciciency of the system.

The authors would like to express our sincere gratitude to Research Organization for Energy and Manufacture, National Research and Innovation Agency that supported to any part of this study.

References

[1] M. Romanello *et al.*, “The 2022 report of the Lancet Countdown on health and climate change : health at the mercy of fossil fuels,” 2022.
[2] Ditjen Mineral dan Batubara, “Road Map Pengembangan dan Pemanfaatan Batubara 2021-2045,” 2021.
[3] Z. Yong, Y. Dong, X. Zhang, and T. Tan, *Renew. Energy*, **78** (2015).
[4] Y. Shen, J. L. Linville, M. Urgun-demirtas, M. M. Mintz, and S. W. Snyder, “An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States : Challenges and opportunities towards energy-neutral WWTPs,” *Renew. Sustain. Energy Rev.*, vol. 50, pp. 346–362, 2015.
[5] R. Huang *et al.*, “Impact of Optimized Flow Pattern on Pollutant Removal and Biogas Production Rate Using Wastewater Anaerobic Fermentation,” *BioResources*, vol. 10, no. 3, pp. 4826–4842, 2015.
[6] C. Nitsos, L. Matsakas, K. Triantafyllidis, U. Rova, and P. Christakopoulos, “Evaluation of Mediterranean Agricultural Residues as a Potential Feedstock for the Production of Biogas via Anaerobic Fermentation,” *Biomed Res. Int.*, vol. 2015, 2015.
[7] Ditjen PLSB3, “Laporan Kinerja Direktorat Pengelolaan Sampah Tahun 2021,” 2022.
[8] D. E. Direktorat Bioenergi, “Pedoman Investasi Pembangkit listrik tenaga bioenergi.” 2021.
[9] K. Martínez-guijarro, A. Ramadan, and B. Gevao, “Atmospheric concentration of polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans (PCDD/ Fs) and dioxin-like polychlorinated biphenyls (dl-PCBs) at Umm-Al-Aish oil field-Kuwait,” *Chemosphere*, vol. 168, pp. 147–154, 2017.
[10] D. F. K. Rawn *et al.*, “Dioxins/ furans and PCBs in Canadian human milk: 2008 – 2011,” *Sci. Total Environ.*, vol. 595, pp. 269–278, 2017.
[11] Z. Chen *et al.*, “Dioxins degradation and reformation during mechanochemical treatment,” *Chemosphere*, vol. 180, pp. 130–140, 2017.
[12] M. Zhan *et al.*, “Suppression of dioxins after the post-combustion zone of MSWIs,” *Waste Manag.*, 2016.
[13] D. Panepinto, G. A. Blengini, and G. Genon, “Economic and environmental comparison between two scenarios of waste management: MBT vs thermal treatment,” *"Resources, Conserv. Recycl.*, vol. 97, pp. 16–23, 2015.

[14] K. Takeishi and R. Krewinkel, “Advanced Gas Turbine Cooling for the Carbon-Neutral Era,” *Int. J. Turbomach. Propuls. Power*, vol. 8, no. 19, 2023.
[15] T. Hoang and D. K. Pawluskiewicz, “The efficiency analysis of different combined cycle power plants based on the impact of selected parameters,” *Int. J. Smart Grid Clean Energy*, vol. 5, no. 2, pp. 77–85, 2016.
[16] N. D. Montiel-bohórquez, A. F. Agudelo, and J. F. Pérez, “Modelling of an Integrated Plasma Gasification Combined Cycle power plant using Aspen Plus,” *J. King Saud Univ. - Eng. Sci.*, no. xxxx, 2022.
[17] W. Lee, H. Oh, J. Lee, M. Oh, and C. Lee, “Performance analysis and carbon reduction assessment of an integrated syngas purification process for the co-production of hydrogen and power in an integrated gasi fi cation combined cycle plant,” *Energy*, vol. 171, pp. 910–927, 2019.
[18] G. Go and U. Moon, “A Water-Wall Model of Supercritical Once-Through Boilers Using Lumped Parameter Method,” *J. Electr. Eng. Technol.*, vol. 9, no. 6, pp. 1900–1908, 2014.
[19] Y. Farahani, A. Jafarian, and O. M. Keshavar, “Dynamic simulation of a hybrid once-through and natural circulation Heat Recovery Steam Generator (HRSG),” *Energy*, vol. 242, p. 122996, 2022.
[20] A. M. H. Putri and A. Widiharto, “Pemanfaatan Biogas dari Pengolahan Sampah TPST Bantar Gebang sebagai Bahan Bakar Pembangkit Listrik,” in *Prosiding Kongres Teknologi Nasional*, 2016, pp. 25–27.