Thermodynamic Modelling of Waste to Energy Power Plant: A Case Study in Makassar City, Indonesia

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Abstract: Waste is a major problem in big cities in Indonesia, one of which is Makassar City. Every year the amount of waste generated by the residents of Makassar City continues to increase, but this is not proportional to the capacity of the landfill. Therefore, researchers want to design a waste-to-energy power plant system in Makassar City or other words apply the waste-to-energy concept. The waste-to-energy concept aims to process waste into energy and reduce the volume of waste in landfills. Then the research method used is thermodynamic modelling using STEAG Ebsilon Professional version 13.02 software. From this analysis it was found that the capacity of the waste that can be burned is 798.3 tons/day, the thermal input of the incinerator is 40.482 MW, the thermal capacity of the boiler is 30,749 MW, the thermal efficiency of the waste-to-energy boiler 77.328 %, the mechanical power of the steam turbine is 10.816 MW, the heat duty of the high-pressure feedwater heater is 1,681.321 kW, the heat duty of the low-pressure feedwater heater is 1,780.234 kW, and the cooling duty of the air-cooled condenser 20.337 MW. This design has a net thermal efficiency of 24.110%, a net plant heat rate of 14,931.515 kJ/kg, an auxiliary load of 912.744 kW, a net plant power of 9.587 Mwe, a specific fuel consumption of 1.214 kg/kWh for each unit at the maximum load, and reducing municipal solid waste generation per year by 291,379.5 tons.

Keywords: Waste to Energy, combustion line, boiler, steam turbine, high-pressure feedwater heater, low-pressure
feedwater heater, air-cooled condenser, heat duty, cooling duty, net thermal efficiency, net plant heat rate, auxiliary load, net plant power, and specific fuel consumption.

1. Introduction

Municipal solid waste is a term usually applied to a heterogeneous collection of wastes produced in urban areas. Generally, urban wastes can be subdivided into two major components: organic and inorganic. The characteristics and quantity of the solid waste generated in a region are a function of the standard of living in the city or country. Wastes generated in developing countries have a large proportion of organic waste, while the wastes in developed countries are more diversified with relatively larger shares of plastics and paper (Sudibyo *et al.*, 2017). Almost all economic sectors generate municipal solid waste. Some factors that influence high municipal solid waste generation are population and economic growth, education, occupation, consumption patterns, and gross domestic product per capita. With a high gross domestic product, Indonesia generates a large amount of annual municipal solid waste in ASEAN countries (Lestari and Trihadiningrum, 2019).

The annual production of municipal solid waste in Indonesia reaches 31 million tons with the waste composition including food waste at 39.23%, plastic at 18.11%, paper at 12.83%, wood at 12.16%, metal at 3.19%, cloth at 2.55%, glass 2.42%, leather 1.82%, and others 7.69% (Ministry of Environment and Forestry Republic of Indonesia, 2022). Meanwhile, Makassar City's annual solid waste production reaches 1,023,710 tons with a composition of food waste at 54.70%, wood at 11.33%, plastic at 12.20%, paper at 6.78%, textile at 1.30%, glass at 1.15%, metal 1.07%, battery 0.62%, rubber 0.42% and other 10.43% (Department of The Environment of Makassar City, 2022). Indonesian municipal solid waste has a high moisture content, volatile matter content, as well as carbon and hydrogen content, and contains more organic matter. Moisture content is a major factor impacting calorific value. The lower heating value on the wet basis of the entire municipal solid waste sample was found to be 8.6 MJ/Kg, which is not only relatively high compared with the average calorific value, but also above the World Bank-recommended calorific value minimum for waste-to-energy applications. In conclusion, municipal solid waste in Indonesia is suitable for waste-to-energy, whether combustion (incineration) or gasification-based (Zhen *et al.*, 2020).

The concept of waste-to-energy aims to process waste into energy and reduce the volume of waste in landfills. The most commonly used technology for converting waste into energy is incineration (Branchini, 2015). This is because incineration technology provides a more productive way of decreasing the amount of urban solid waste that needs to be landfilled. The incineration of municipal solid waste can minimize its mass by 70% and volume by 90%, as well as electricity and heat recovery (Cudjoe and Acquah, 2021). The purpose of this research is to get a waste-to-energy power plant model that is suitable and can solve the waste problems in Makassar City.

2. Fuel From Waste

Makassar City has a daily potential power from the waste of 24.882-33.768 MWe with an LHV variation of 7-8.6 MJ/kg and an average amount of waste of 1,023,710 $tons/day$ in 2021. Makassar City municipal solid waste production data can be seen in the table below.

Table 1 Makassar City municipal solid waste production data (Department of The Environment of Makassar City, 2022).

Year	Daily $(tons/day)$	Yearly $(tons/year)$
2008	386.826	141,191.490
2009	456.318	166,556.070
2010	532.744	194,451.560
2011	529.878	193,405.470
2012	557.312	203,418.880
2013	676.632	246,970.680
2014	677.213	247,182.745
2015	674.716	246,271.340
2016	651.649	237,851.885
2017	795.129	290,222.085
2018	707.923	258,391.895
2019	696.585	254,253.525
2020	996.710	363,799.150
2021	1,023.710	373,654.150
Total	3,417,620.925	

3. Waste To Energy Power Plant Description

The Makassar City waste-to-energy power plant model consists of two identical units. Each of the two waste-to-energy power plant units has a high-pressure feedwater heater, a low-pressure feedwater, a deaerator, a steam turbine, an electric generator, a boiler, and four air-cooled condenser units. The estimated incinerator capacity of this power plant is 842.7 tons per day with an estimated power that can be generated of 20,482 – 25,164 MWe. The technical data of the Makassar City waste-to-energy power plant model is shown below.

Table 2 Combustion Parameters (Liu et al., 2020), (Strobel, Waldner and Gablinger, 2018).

Minimum combustion temperature (℃)	850
Maximum combustion temperature (℃)	1450
Primary combustion zone air ratio	<1.2
Secondary combustion zone air ratio	1.7

Table 3 Steam and Water Cycle Parameters (Babcock & Wilcox Company, 2005), (Teir, 2003).

Economizer working pressure (bar)	93.342
Evaporator working pressure (bar)	93.342

Superheater working pressure (bar)	90.623
Economizer working temperature (℃)	250
Evaporator working temperature (℃)	305.974
Superheater working temperature (℃)	449
Economizer pressure drop (bar)	7.468
Evaporator pressure drop (bar)	14
Superheater pressure drop (bar)	0.020

Table 4 Boiler Ratings (Ozawa and Asano, 2021), (Branchini, 2015).

Air ratio	1.2
Circulation ratio	5
Air Fuel Ratio for LHV 8.6 MJ/kg	4.125
Flue gas recirculation ratio (%)	15

Table 5 Steam turbine parameters (Siemens AG, 2019).

Steam turbine type	Siemens SST-200
$h_1 (kJ/kg)$, with T=447.464 °C and P=88 bar	3,254.308
$h_2 (kJ/kg)$, with T=337.839 °C and P=40 bar	3,062.643
$h_3 (kJ/kg)$, with T=337,839 °C and P=40 bar	3,062.643
$h_4 (kJ/kg)$, with T=231,363 °C and P=16 bar	2,874.053
$h_5 (kJ/kg)$, with T=231.363 °C and P=16 bar	2,874.053
$h_6 (kJ/kg)$, with T=170.414 °C and P=8 bar	2,751.521
$h_7 (kJ/kg)$, with T=170.414 °C and P=88 bar	2,751.521
$h_8 (kJ/kg)$, with T=60.059 °C and P=0,2 bar	2,249.696
Isentropic efficiency (%)	88.0
Mechanical efficiency (%)	98.0
Steam turbine speed (rpm)	7,300
Gear box speed (rpm)	3,000
Controlled extraction	Up to 4
Condensing pressure for air-cooled condenser $(bar\ abs)$	0.2

4. Modelling And Simulation of Waste to Energy Power Plant

The modelling process is carried out by entering the technical data of the waste power plant into the model that the researchers have created (as shown in Figure 1). After entering technical data into the model, a simulation process is carried out to determine the performance of the model at the maximum load of each unit, which is 10.5 MWe. The performance observed in the model is the amount that can be burned, the thermal capacity of the boiler, the mechanical power of the steam turbine, the heat duty of the high-pressure feedwater heater, the heat duty of the low-pressure feedwater heater, the cooling duty of the air-cooled condenser, net thermal efficiency, net plant heat rate, auxiliary load, net plant power, and specific fuel consumption.

The equation used to calculate the net thermal efficiency of the model is as follows (Black and Veatch, 1996):

$$\eta_{th} = \frac{3{,}598\ (kJ)}{Net\ plant\ heat\ rate\ \left(\frac{kJ}{kWh}\right)} \tag{1}$$

The equation used to calculate the net plant heat rate is as follows (Black and Veatch, 1996):

$$NPHR = \frac{(\dot{m}_{fuel} \times LHV)\ 3{,}598\ (kJ)}{(Gross\ plant\ power(kW) - Auxiliary\ power(kW))} \tag{2}$$

The equation used to calculate specific fuel consumption is as follows (Hoval Company, 2013):

$$SFC = \frac{Net\ plant\ heat\ rate\ \left(\frac{kJ}{kWh}\right)}{LHV\ \left(\frac{kJ}{kg}\right)} \tag{3}$$

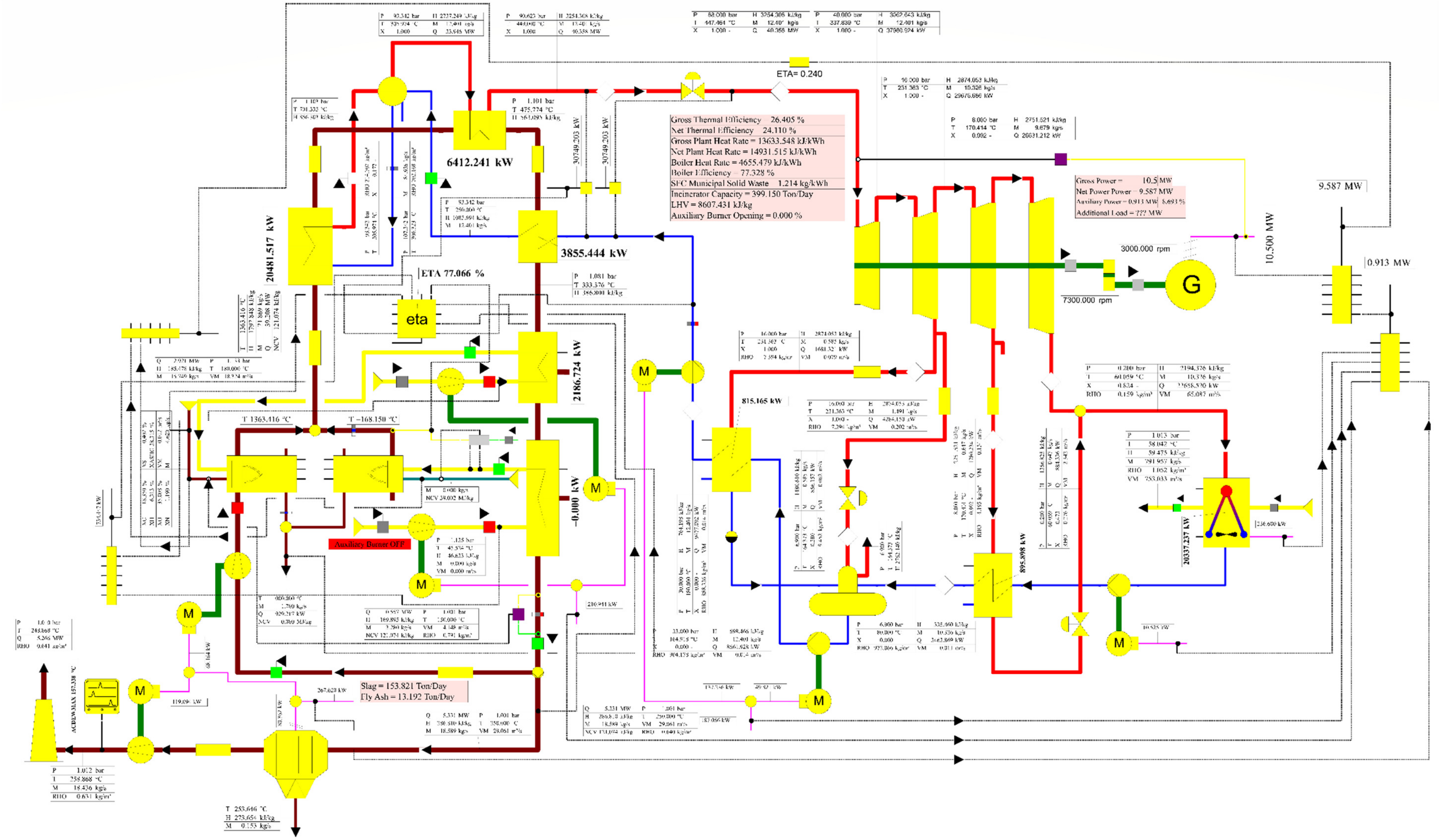

Figure 1. Model of waste-to-energy power plant system using STEAG Ebsilon Professional.

5. Result and Discussion

After conducting a simulation of the waste power plant model as shown in Figure 1, the researchers got the results for each unit shown in table 6.

Table 6 Simulation results of the waste-to-energy power plant model for each unit.

Waste-to-energy power plant system	
Gross thermal efficiency (%)	26.405
Net thermal efficiency (%)	24.110
Gross plant heat rate (kJ/kWh)	13,633.548
Net plant heat rate (kJ/kWh)	14,931.515
Specific fuel consumption (kg/kWh)	1.214
Gross plant power (kW)	10,500.000
Net plant power (kW)	9,587.256
Auxiliary power (KW)	912.744
LHV (MJ/kg)	8.6
Boiler	
Boiler thermal efficiency (%)	13,633.548
Boiler heat rate (kJ/kWh)	77.328
Firing rate (ton/day)	399.150
Combustion air (ton/h)	56.698
Combustion temperature (℃)	1,363.416
Thermal input (kW)	40,482.963
Economizer heat load (kW)	3,855.444
Evaporator heat load (kW)	20,481.517
Superheater heat load (kW)	6,412.241
Air preheater heat load (kW)	2,186.724
Net boiler power (kW)	30,749.203
Exhaust losses (kW)	6,964.167
Slag losses (kW)	2,032.714
Radiation losses (kW)	153.523
Uncountable losses (kW)	583.357
Total heat losses (kW)	9,733.760
Maximum acid dew point (℃)	157.338
Slag (ton/day)	153.821
Fly ash (ton/day)	13.192
Steam turbine	
Inlet mass flow rate (kg/s)	12.401
Extraction 1 mass flow rate (kg/s)	2.076
Extraction 2 mass flow rate (kg/s)	0.647
Exhaust stage mass flow rate (kg/s)	9.679
Gross mechanical power (MW)	10,816.267

Net mechanical power (MW)	10,652.328
Transmission losses (MW)	98.484
Transmission efficiency (%)	163.938
High-pressure feedwater heater	
Hot side mass flow rate (kg/s)	0.585
Cold side mass flow rate (kg/s)	12.041
Heat duty (kW)	1,681.321
Heat load (kW)	815.165
Low-pressure feedwater heater	
Hot side mass flow rate (kg/s)	0.647
Cold side mass flow rate (kg/s)	10.326
Heat duty (kW)	1,780.234
Heat load (kW)	895.898
Air-cooled condenser	
Hot side mass flow rate (kg/s)	10.326
Cold side mass flow rate (kg/s)	791.957
Cold side outlet temperature (℃)	58.042
Heat load (MW)	22,658.250
Cooling duty $\left((MW)\right)$	20,337.237
Total required power for fans (kW)	236.600
Electric generator	
Real power (MW)	10.500
Idle power $(MVAR)$	5.085
Apparent power (MVA)	11.666

5.1 Waste to Energy Power Plant Efficiency

From the simulation results, it can be seen that the net thermal efficiency of the waste-to-energy power plant system model is 24.110%. These results are following research conducted by Mutz et al. (2017) which states that in general the thermal efficiency of waste power plants is 20% this is in line with research conducted by Branchini (2015) which states that in general the thermal efficiency of waste power plants ranges from 18% to 25% and in some cases more than 30%.

In addition, the model of the waste power plant system created by the researchers also uses a low air ratio to increase the net thermal efficiency of the waste power plant. This is in line with research conducted by Strobel, Waldner and Gablinger (2018) which states that another benefit of using a low air ratio in a waste power plant is an increase in thermal efficiency.

5.2 Waste to Energy Boiler Efficiency

From the simulation results, it can be seen that the boiler thermal efficiency obtained is 77.328 %. These results are slightly lower than the results of research conducted by Schu and Leithner (2008) which state that the efficiency of the thermal waste-to-energy boiler is around 83%. The cause of the boiler thermal efficiency of the waste power plant system design made by researchers is slightly lower than the research conducted by Schu and Leithner (2008) is the high temperature of the flue gas released into the atmosphere through the stack, which is 250 ℃. This happens because the model of a waste-to-energy power plant system made by researchers uses a convective superheater in a boiler which places the superheater after the evaporator which causes the temperature of the flue gas coming out of the convective superheater to be higher than the temperature of the steam coming out of the superheater (more than 449 °C). The different results will be obtained if the design of a waste power plant uses a radiant superheater which allows the temperature of flue gas released into the atmosphere through the stack to be lower than a temperature of 250 °C which of course will increase the boiler thermal efficiency.

In addition, the cause of the high flue gas temperature released into the atmosphere through the stack is the maximum acid dew point of the flue gas produced by the waste fuel combustion process which is 157.338 °C. So that the temperature of the flue gas released into the atmosphere through the stack cannot be lower than the maximum acid dew point.

5.3 System Heat Balance

From the simulation results, it can be seen that the model of the waste-to-energy power plant system experiences the greatest heat losses in the air-cooled condenser and stack. The Sankey diagram of the model of the waste-to-energy power plant system can be seen in Figure 2. The heat losses that occur in the air-cooled condenser are 20.337 MW or 50.237 % of the system. This happens because all the steam that has been used by the steam turbine and closed feedwater heater is flowed into the water-cooled condenser to change the phase from steam to water by removing the latent heat from the steam. So that the steam that has changed phase to water can flow back to the boiler. The heat losses that occur in the stack (exhaust losses) are 7.8 MW or 17.203 %. This happens because the temperature of the flue gas released into the atmosphere through the stack is high, which is 250 °C which then causes a lot of heat to be wasted from the flue gas.

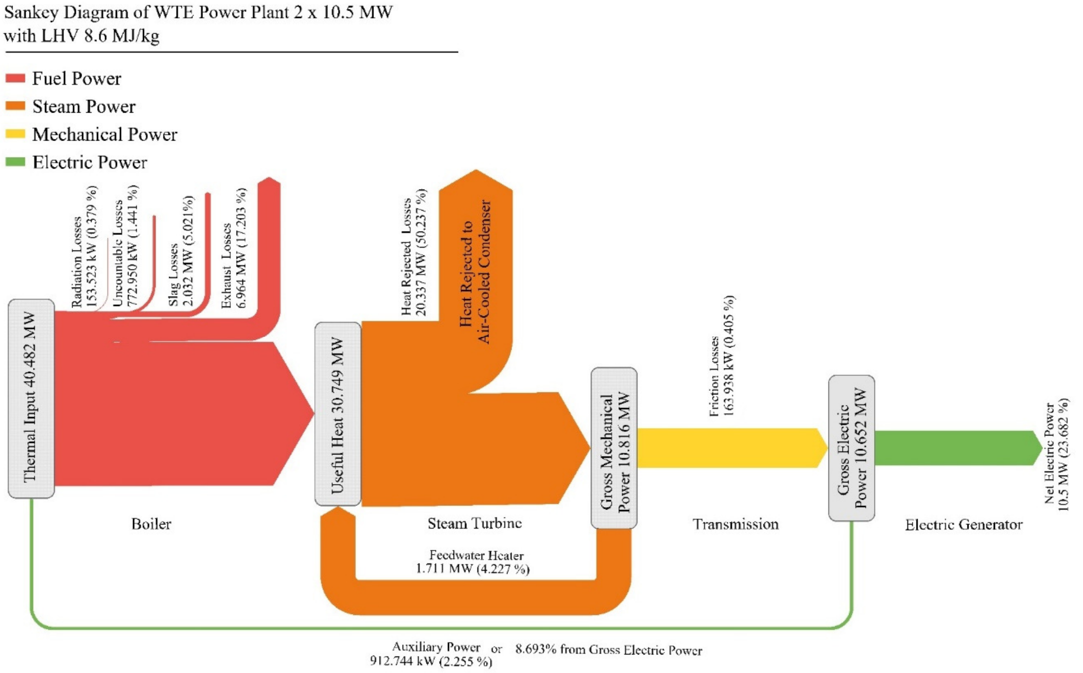

Figure 2. Sankey diagram from the model of waste-to-energy power plant system.

6. Conclusions

The method presented in this paper is thermodynamic modelling using STEAG Ebsilon Professional software version 13.02. The model of the waste-to-energy power plant for Makassar City has an incinerator daily capacity of 399.150 (ton/day) at the maximum load of 10.5 MWe for each unit, the thermal capacity of the waste-to-energy boiler is 30,749 MW, the thermal efficiency of the waste-to-energy boiler is 77.328 %, the thermal efficiency of the waste-to-energy boiler, the mechanical power of the steam turbine is 10.816 MW, the heat duty of the high-pressure feedwater heater is 1,681.321 kW, the heat duty of the low-pressure feedwater heater is 1,780.234 kW, and the cooling duty of the air-cooled condenser 20.337 MW, the net thermal efficiency is 24.110%, the net plant heat rate is 14,931.515 kJ/kWh, the auxiliary load is 912.744 kW, a net plant power of 9.587 MWe, the specific fuel consumption is 1.214 kg/kWh with LHV 8.6 MJ/kg. This waste-to-energy power plant model is suitable to be implemented and can solve waste problems in Makassar City.

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