Part II of II

Palm Oil Mill Effluent (POME): Biogas Power Plant

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ABSTRACT

Indonesia is the largest palm oil producer in the world. The palm oil mills process fresh fruit bunches (FBB) and produce two main products: Crude palm oil (CPO) and palm kernel oil (PKO). The process generates abundant waste water called palm oil mill effluent (POME). The POME is then converted into biogas through a gasification process. The biogas is used to fuel gas engine and generates electricity. This article presents the technical and economic analysis of a biogas power plant in Indonesia. Also, it analyzes waste heat recovery potential from biogas engine.

PERFORMANCE OF BIOGAS POWER PLANT

Typically, biogas consist of predominantly methane (CH_4), carbon dioxide (CO_2), a small amount of nitrogen, and hydrogen sulfide (H_2S). This composition shows biogas quality. The methane content in biogas is the most important element since it is the only combustible element. The higher the methane content, the higher the quality of biogas. The methane content in biogas under study is between 55% and 65%. In addition to methane, carbon dioxide (CO_2) is the second largest element in biogas. The presence of CO_2 in biogas reduces the biogas heating value. The carbon dioxide composition in biogas power plant under study is between 32% and 45%. Another element in biogas is hydrogen sulfide (H_2S). The level of hydrogen sulfide of raw biogas is usually above 1500 ppm. At a level higher than 1000 ppm, the H_2S could deteriorate the engine and the mechanical system due to corrosion process. The high level of H_2S may also reduce engine reliability and lifetime, and increase the maintenance cost [5]. The highest permissible level of H_2S in the gas engine is 200 ppm. A scrubber is used to remove H_2S and maintain the H_2S level below 200 ppm.

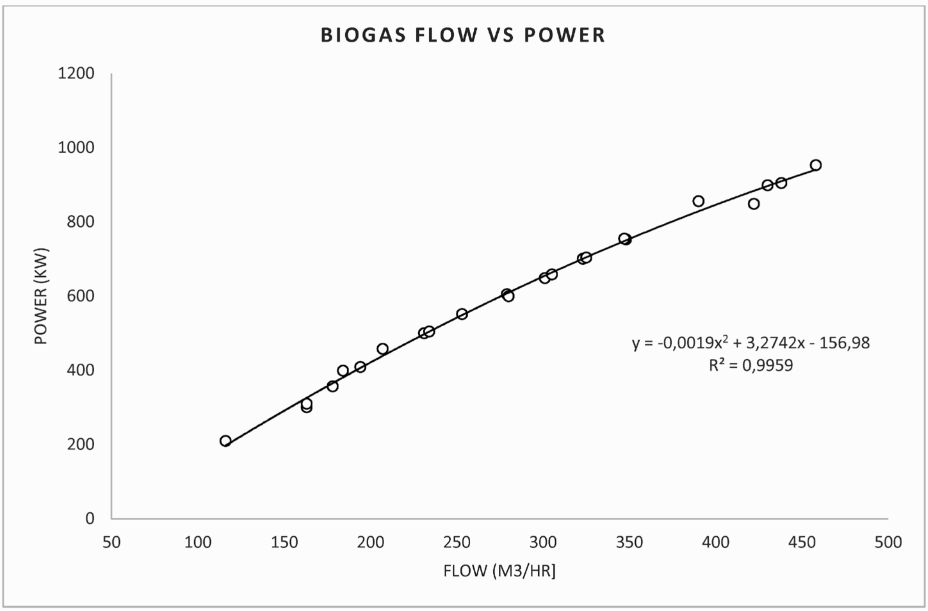

Figure 3. Biogas flow vs electricity power output

Biogas quantity is usually in the form of volumetric rate (m^3/hr). To generate electricity through a gas engine, both the quality and quantity of biogas must be able to meet the demand load. The performance of biogas power plant is often expressed in kWh/m^3 (Figure 3). Every 1 m^3 of biogas can generate electricity between 1.8 and 2.1 kWh. Low-quality biogas may consume more biogas to meet the specified load demand. On the other hand, high-quality biogas needs less biogas at the same load.

There are several factors affecting biogas quality and quantity. These factors are an anaerobic process and the characteristic of POME. Biogas potential of the raw material, pH, temperature of the anaerobic process, hydraulic retention time (HRT) and carbon to nitrogen ratio (C/N ratio) plays a significant role in biogas quality and quantity. C/N ratio affects the volume of biogas production by controlling the pH value of slurry [12]. Controlling these factors can stabilize the quality and quantity of biogas production.

The biogas power plant efficiency varies with load. Figure 4 shows the relationship between biogas power plant load and its efficiency. The efficiency range between 29% (210 kW) and 35% (755 kW) with average efficiency 33.6%. The efficiency is affected by biogas composition (biogas quality). It is difficult to precisely control the air to fuel ratio when the biogas composition varies [13]. A proper air to fuel ratio is essential to obtain the best combustion efficiency. The trend in Fig 4 shows that biogas efficiency increases as the load increases. However, the biogas efficiency is slightly lower than that of natural gas or diesel engine. Typical efficiency of internal combustion engine is between 38% and 40% [10, 11].

The efficiency shown in Figure 4 is a gross efficiency. It does not consider the auxiliary power consumption. The auxiliary power consumption is tabulated in Table 2 at different load. The auxiliary power consumption is used to electrify auxiliary equipment in biogas plant system and biogas engine system. The auxiliary equipment are such as an influent pump, a receiving sump pump, a cooling tower pump, a chemical pump, primary feed pumps, a sludge pump, a discharge pump, a compressor (for instrumentation), a gas blower, a humidifier/dryer, office, lightings, and engine auxiliary equipment. Auxiliary power consumption should be taken into account to calculate the net efficiency of biogas power plant. The ratio of auxiliary power to power output is between 8% and 10%. The average auxiliary power consumption is about 68 kW or 9% of biogas engine power output (at 789 kW engine power output).

Table 3 shows the net efficiency of biogas power plant. Without considering auxiliary power consumption, the gross efficiency of biogas engine is around 34.14% at 856 kW. There is about 2.7 % difference in engine efficiency. Therefore, it is important to consider auxiliary power consumption into efficiency calculation.

Table 2. The auxiliary power consumption of the biogas power plant system.

Day	Power (kW)	Auxiliary Power (AP) (kWh)	AP/Power (%)
1	778	58	8%
2	801	67	8%
3	757	57	8%
4	755	68	9%
5	772	72	9%
6	810	80	10%
7	786	71	9%
8	856	68	8%

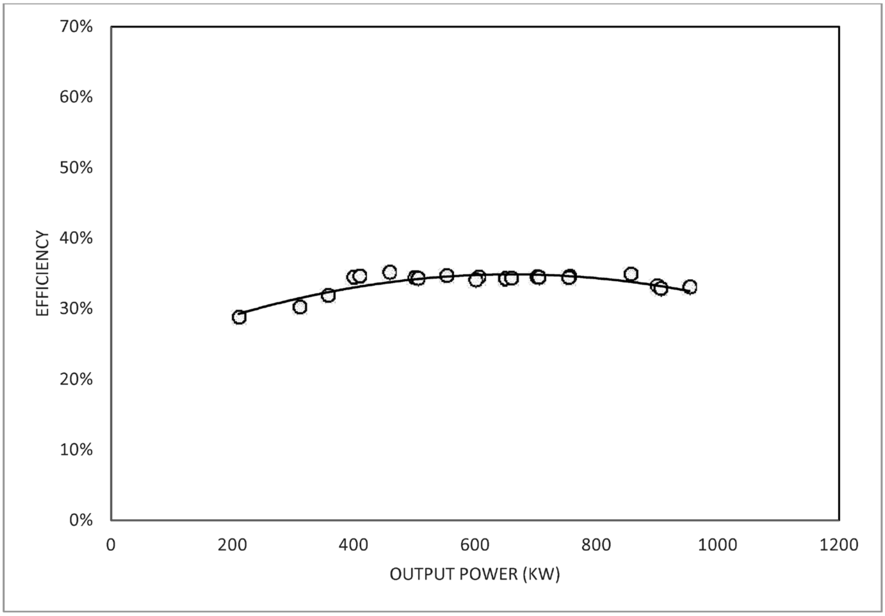

Figure 4. Efficiency of biogas engine at different load

WASTE HEAT RECOVERY POTENTIAL

Table 3. Net efficiency of biogas engine

Biogas Flow	398	m^3/hr
Energy content	6.3	kWh/m^3
Output power	856	kW
Auxiliary power	68	kW
Gross efficiency	34.14%	%
Net efficiency	31.43	%

Exhaust temperature from biogas engine is between 573°C and 653°C at 30% to 95% of engine load, as shown in Figure 5. The high exhaust temperature is caused by the properties of biogas itself. Biogas has high fire temperature, slower burning speed, and severe ignition delay [14]. Also, the presence of carbon dioxide in biogas slow down the combustion velocity [15]. Therefore, some part of biogas is burned out completely in a combustion chamber (piston), and the other part of biogas is burned out in the post-combustion period [15]. Moreover, there is some part of biogas fuel burning in exhaust region [15]. All of these factors contribute to a lower efficiency of biogas engine. Consequently, the flue gas temperature is also higher. Fortunately, a high exhaust gas temperature is a potential source for waste heat recovery.

In addition to the exhaust gas, there are other sources of waste heat from biogas engine. These sources are waste heat from water jacket (primary cooling circuit), low-temperature cooler, oil cooler, and radiation loss. The energy and mass balance show that total energy loss from biogas engine is 67% of energy input. Heat losses from the exhaust gas, water jacket, and oil cooler contribute to 45%, 37%, 5% of total energy loss, respectively. Other losses come from a low-temperature cooler, oil cooler, and the radiation loss which is relatively small. The radiation loss only accounts for 7% of total energy loss (Figure 6).

The recoverable of waste heat depends on its quality. The quality of waste heat is determined by its temperature. The higher the waste heat temperature, the higher the quality of heat waste. Also, the quantity of waste heat source plays an important role but not as important as temperature. Based on this criteria, the potential waste heat sources for heat recovery are exhaust gas, oil cooler, and water jacket. The waste heat can be used to heat boiler feedwater. Simple analysis will be performed to assess the possibility of waste heat utilization.

Pre-Heating Boiler Feedwater

The biogas power plant is located near to the palm oil mill facilities. The palm oil mill facility processes 50-60 Ton/hr FFB and has a biomass power plant. The biomass power plant uses palm oil shell and fiber as fuel, and it has one boiler and two steam turbines. The boiler produces 36 Ton/hr of steam at temperature 260°C and pressure 20 Bar. The boiler is used to provide steam for palm oil milling process and generating electricity through 2 x 850 kW steam turbine. The location of the biomass power plant is about 150 meter from biogas power plant. Therefore, the waste heat utilization to heat boiler feedwater might be possible and attractive.

The first alternative for heating feedwater is shown in Figure 7. The waste heat from water jacket heats the boiler feedwater. The Boiler feedwater temperature may increase by 15.6°C. Then, the boiler feedwater could be further heated by the exhaust gas. Then the boiler feedwater temperature may rise by 15°C. Total energy recovered by boiler feedwater is about 1285 kW, and it increases the feedwater temperature by 30.76°C.

There is an additional waste heat source for further heat recovery; it is an oil cooler (Figure 8). The final temperature of boiler feedwater can increases by 3.8°C compared with first configuration above. Total energy recovered by boiler feedwater is about 1411 kW, and it increases the feedwater temperature by 33.8°C. This low increase in temperature is caused by the properties of the oil. Engine oil has a half specific heat of water.

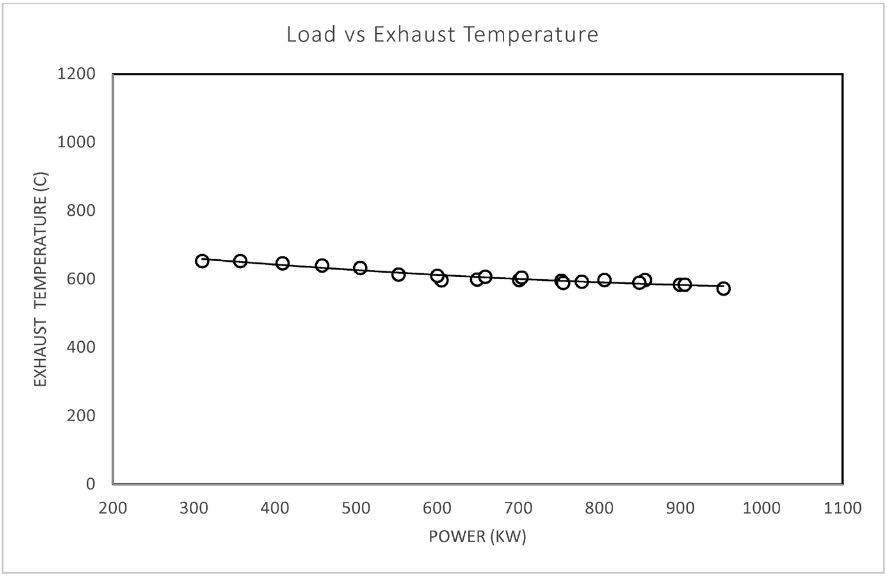

Figure 5. Exhaust temperature of biogas engine

Therefore the ability to store heat is lower. However, waste heat recovery application from oil cooler should be studied in more detail in a full feasibility study. Further study should address whether 3.8°C increases in feedwater temperature would be comparable to the investment incurred.

The acid dew point temperature limits the cooling of exhaust gas. The sulfur content in biogas influences the acid dew point. The higher the sulfur content, the higher the acid dew point. One of the element contains sulfur in biogas is H_2S (Hydrogen sulfide). High level of H_2S indicates a high level of sulfur. For H_2S level below 1000 ppm, the acid dew point is around 150°C [16]. Fortunately, the biogas scrubber is designed to lower the H_2S below 200 ppm. With this low H_2S level, the exhaust gas could be cooled to as low as around 100°C [16]. However, by cooling exhaust gas to 150°C, our assumption is conservative enough.

ECONOMIC OF BIOGAS POWER PLANT

The production cost of power generation depends on these following factor: capital cost, fuel cost, operation and maintenance cost (O&M), a capacity factor of biogas power plant. The capital cost depends on the

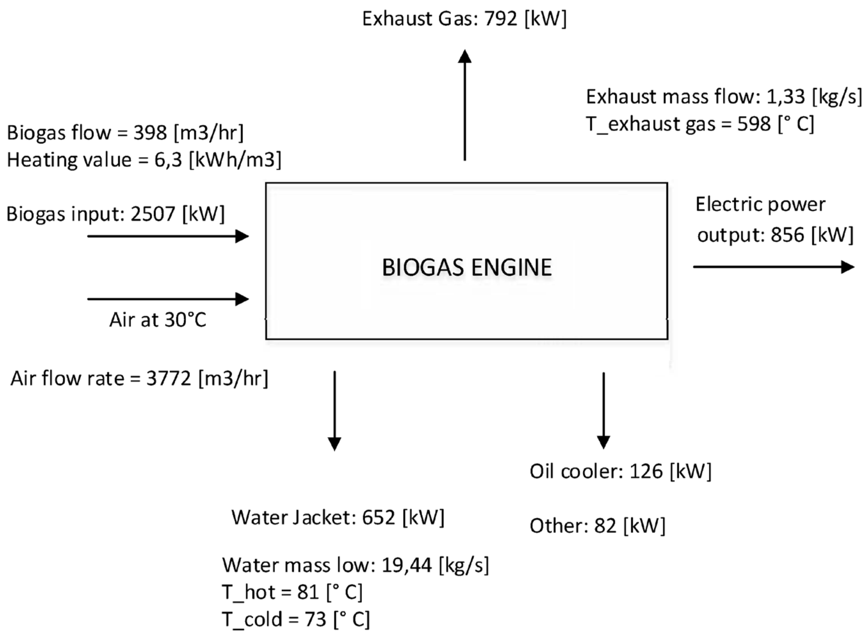

Figure 6. Energy balance of biogas engine

plant size. The larger the biogas power plant size, the lower the capital cost per kW. Fortunately, the fuel cost of biogas is negligible since it is free. Therefore, the electricity production cost is only influenced by the capital cost i.e.: O&M cost, and the capacity factor.

One of the economic analysis tools for power generations is a levelized cost of energy (LCOE), also known as a Levelized Cost of Electricity (LCOE), and Levelized Energy Cost (LEC). The LCOE is the present value of the electricity unit cost over the lifetime of a power generation [17]. In another word, LCOE is the total cost of installing and operating of a power generation over its lifetime and expressed in dollars per kilowatt-hour of electricity produced. Thus, the LCOE is the lowest price at which electricity must be sold for a power plant project to break even. The LCOE is mainly used for comparing different power generation technologies in power generation business. In this paper, the economic of biogas is compared to diesel power plant and utility electricity tariff. Because the utility electricity tariff represents the present cost, for simplicity the Simple Levelized Cost of Energy (SLCOE) is used for the analysis instead of the LCOE. The formula for calculating the SLCOE is as follows [18]:

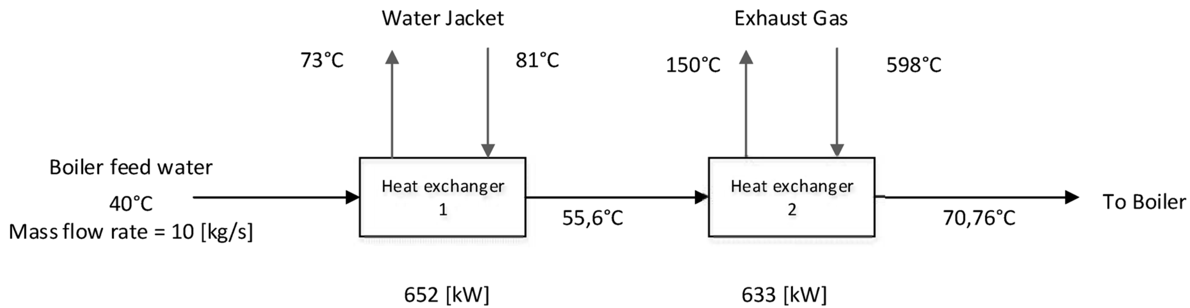

Figure 7. Heat recovery from water jacket and exhaust gas

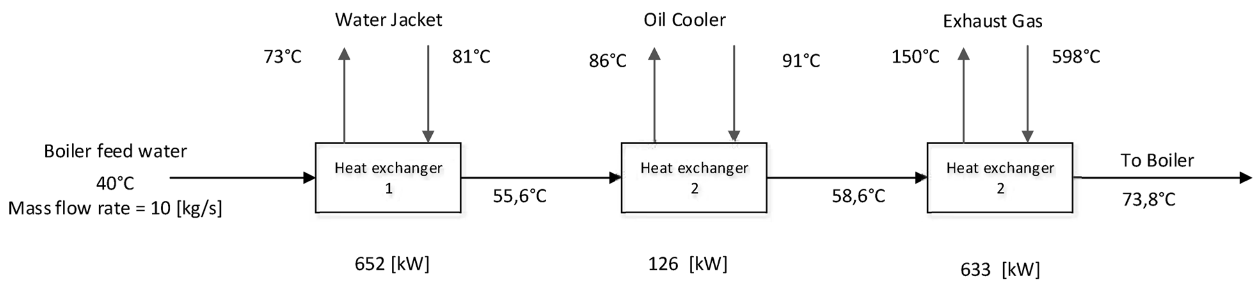

Figure 8. Heat recovery from water jacket, oil cooler, and exhaust gas

$$\text{SLCOE}=\left(\frac{\text{capital cost}\times\text{CRF}+\text{fixed O\&M cost}}{8760\times\text{capacity factor}}\right)+$$

$$(\text{fuel cost}\times\text{heat rate})+\text{variable O\&M cost} \quad (1)$$

Where the CRF is the capital recovery factor. To calculate the CRF, one may use the following formula:

$$CRF=\frac{i\cdot(1+i)^n}{\left((1+i)^n\right)-1} \quad (2)$$

Diesel power generations fulfill most electricity consumption at palm oil mills in Indonesia. However several palm oil mills use both biomass power plant and diesel power plant to meet their electricity needs. A diesel power plant has a lower capital cost but a higher fuel cost. SLCOE of the diesel power plant is about \$0.23/kWh (Table 5). On the other hand, biogas power plant has a lower electricity generating cost (SLCOE). Replacing diesel power plant with biogas power plant would give significant cost savings. The cost saving makes the biogas power plant has a payback period less than two years. If the payback period is based on the investment cost paid by income from biogas power plant, the project would have a payback period less than three years. Another study states that the biogas power plant has a payback of 4.3 years [19].

Table 4. Breakdown of capital cost

No	Scope of works	% cost
1	Biogas plant	44%
2	Civil work	10%
3	Biogas purification	10%
4	Biogas engine	19%
5	Waste water treatment	10%
6	Others	8%
	Total	100%

Biogas power plant has a right to sell their electricity to PT. PLN (the only electrical utility company in Indonesia). In 2014, the Power Purchase Agreement (PPA) tariff for a biogas power plant was about \$0.094/kWh (Rp.1323/kWh) [20]. The PPA price is slightly higher than generation cost as shown in Table 5. With this price, it is also attractive to invest in a biogas power plant and then sell the electricity to a utility company. Currently, the Indonesia government has issued a new PPA tariff for biogas power plant. The PPA tariff is about \$0.122/kWh for the Sumatera region [21]. The new tariff makes biogas power plant much more attractive.

According to Table 5, the capital cost has the greatest effect on production cost. The capital cost includes the biogas plant and the gas engine system. The biogas engine system cost is about 19% of total investment (Table 4). On the other hand, the biogas plant cost is about 44% of total investment cost (Table 4). The rest of the investment goes to the civil works, water treatment plant and others (Table 4).

The biogas capacity factor is about 65.8%. It is low compared to that of using other fuels such as diesel engine (Table 5). Several factors cause low capacity factor of biogas power plant. Firstly, the biogas rarely operates at 100% load. The system may oversize or have lower biogas production than expected. Therefore, the engine rarely operates more than 90% load. Secondly, failures have caused the biogas power plant system to shut down frequently. Consequently, it increases unnecessary downtime. The long-term improvement planning should be introduced to increase the capacity factor by solving these two problems.

Economic Analysis of Waste Heat Recovery Potential

The energy and fuel saving from heat recovery application are calculated as following:

$$energy\ savings = \frac{Heat\ recovery\ (kW)}{Boiler\ Efficiency} = \frac{1411\ [kW]}{0{,}7} = 2016\ kW$$

$$Fuel\ savings = \frac{Energy\ Savings}{LHV\ of\ Shell\ and\ Fibre} x8760\ [hr]xCF$$

$$Fuel\ savings = \frac{2{,}016\ [kW]}{4.07\ [\frac{kWh}{kg}]} x8760\ [hr]x\ 65.8\%$$

$$Fuel\ savings = 2{,}855\ \text{Ton/year}$$

The energy savings from heating boiler feedwater is around 2 MWh per hour by assuming boiler efficiency is around 70%. The palm oil shell has an energy content around 4.07 kWh/kg [22]. By heating the feedwater, the need of boiler fuel (Shell) is reduced by 7%. This saving is equal to 2,855 Ton of shell annually. The actual fuel saving might be higher than 7% since the calculation is made based on 65.8% of capacity factor and 85% of load. In addition, the total efficiency of combined heating and power is up to 90%.

Table 5. Comparison of electricity cost among biogas power, diesel power & utility.

No	Parameter	Biogas	Diesel	Utility	Unit
A	INPUT DATA				
1	Unit cost	2300	600		USD/kW
2	Capacity	1,000	1,000		kW
3	Capital cost	2,300,000	600,000		USD
4	Capacity factor	65.8%	82.2%		%
5	Interest	10%	10%		%
6	Period	8	8		Years
7	O&M unit cost	0.015	0.01		USD/kwh
8	Specific fuel consumption		0.3		liter/kwh
9	Fuel cost		0.69		USD/liter
B	CALCULATION				
10	Capital Recovery Factor	0.187444	0.187444		
11	Energy production	5,760,000	7,200,000		kWh/year
12	Capital cost payment	0.075	0.016		USD/kWh
C	PRODUCTION COST				
13	Capital cost payment	0.075	0.016		USD/kWh
14	O&M Cost	0.015	0.01		USD/kWh
15	Fuel Cost		0.208		USD/kWh
16	Total Production cost	0.090	0.233		USD/kWh
17	Utility electricity price			0.125	USD/kWh
C	SAVINGS				
17	Savings		0.143	0.035	USD/kWh
18	Percentage saving		61%	28%	%

The palm oil shell is usually not for sale in Indonesia. The palm oil shell price (FOB price) is around US$ 38/Ton [23]. Therefore, the estimated fuel cost saving is about US$ 108,403/year. The Investment cost is estimated around US$ 250,000. With this cost savings, the payback period is expected to be less than three years. Therefore, the heat recovery application at biogas power plant is very economically attractive.

However, a detailed feasibility study should be performed to assess the technical and economic issues of heat recovery application. Matching the load between waste heat and boiler load based on historical data should be evaluated adequately to estimate saving more accurately and to size the heat recovery system. Again, the result should provide high accuracy of the analysis in term of economic and technical.

CONCLUSION

The operation and performance of biogas power plant have been studied and analyzed. The performance analysis shows that the biogas engine has a gross efficiency between 29% (20% Load) and 35% (75% load). The average efficiency is about 33.6%. Considering the auxiliary power consumption would reduce the efficiency by 2.7% (at 85% Load). The auxiliary power consumes averagely 9% of electricity generated. There is also potential application for waste heat recovery by heating the boiler feedwater. Heating the boiler feedwater reducing the boiler fuel consumption by 7%.

The economic analysis shows that biogas power plant is economically competitive power generation. The production cost of biogas power plant is US$ 9 cent/kWh. Replacing the diesel engine with biogas power plant would generate cost saving by 61%. Comparison with the utility electricity tariff shows the electricity cost of biogas is 28% cheaper than utility tariff. In addition, applying waste heat recovery technology for boiler feedwater heating could reduce the boiler fuel consumption. The investment for waste heat recovery equipment has a payback period less than 3 years.

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