Waste Heat Potential Assessment of The Engine Based Power Plant in Thai Palm Oil Mills

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***Abstract*— Renewable energy (RE) and energy efficiency will be key to achieving sustainability. Biogas from palm oil mill effluent (POME) is an important RE resource. Thailand is the third-ranked in the world leading palm oil producers after Malaysia and Indonesia. In the last decade, Thai palm oil mills (POMs) have produced biogas which is used as fueled in engine power plants supporting the country's RE program. The spark-ignition (SI) engines are typically used as the prime movers for the power generation, and their thermal fuel efficiency may range 28-42% of the energy input, whereas the remaining 58-72% converted to waste heat and dumped into the environment as thermal pollution. The aim of this study was to assess the waste heat potential of the engine power plants in Thai POMs by using a case study approach. The secondary data are collected from the mill and used as a baseline for the assessment. The results show that the electrical efficiency of the engine and actual capability of the engine power generation in Thai POMs are 38.48% and 333.57 GWh. The recoverable or usable thermal energy is 326.49 GWh or 37.67% of the fuel energy or equivalent saving 136,440 tons a year of biomass-fueled in Thai POMs. It has resulted from waste heat potential 384.11 GWh, with assumption effectiveness in 0.85.**

Keywords—bio-gas; engine power plant; palm oil mill; waste heat recovery

I. INTRODUCTION

Renewable energy (RE) and energy efficiency are set as a key role in the sustainability. Thailand is located in the Southeast Asia and in tropical and equator region where is suitable for the oil palm tree plantation [1]. Thailand is ranked in the third of the largest world crude palm oil (CPO) producers after Malaysia and Indonesia. Thai palm oil mills (POMs) consumed 11.02 million tons of fresh fruit bunches (FFB) in 2015 [2]. There are two types of the palm oil mills: dry and wet processing mills [3], [4]. These dry processing mills normally apply with small scale in rural or villages, and they require only heat from the hot air to extract the oil from fruits. Whereas the wet processing mills apply with medium and large mills, which over 10 tons FFB per hour of capacity [3], and they are mostly located in the South of Thailand. The wet processing mills largely require steam and hot water for the oil extraction, mainly used in the sterilization, digestion and clarification process [3], [4].

Total Thai FFB production, 91% is fed to the wet processing mills, and enormous by-products or bio-wastes have generated in each year from these plants. The bio-wastes are both robust and liquid; the solid wastes are palm fiber (PF), empty fruit bunch (EFB) and palm kernel shell (PKS) whereas the liquid waste is palm oil mill effluent (POME). These bio-wastes have been identified as RE resource of the country [5]-[7].

The PF is normally mainly used as fuel in the boiler plant for steam generation, while the EFB and PKS are sold out to be used as biomass fuel for other applications, whereas the POME is drained out to the waste water pond and utilized as either fertilizer or biogas [3]-[5]. In the past, the POME was drained and collected in an opened waste water pond, where the methane is generated by the anaerobic digestion reaction. Methane is a potent greenhouse gas (GHG), which caused the global warming. Sustainability plays a key role in pushing and resolving the problems by transforming the POME to biogas. The POME biogas production has been gradually developed and adopted in several leading CPO producer countries such as Thailand, Malaysia, Indonesia and Nigeria [10]-[13]. The first Thai POME biogas plant has operated since last decade under government subsidized project [14]. In 2015, there were about 41 factories of wet processing POMs under the cooperation Thai biogas project using the POME biogas which is used as fuel in the engine based power plants and generating the power to the grid for supporting the country's RE scheme. Spark-ignition (SI) engines are normally used as prime movers for the power generation. The electrical efficiencies of the engines may range from 28 to 42% [15], [16]. Thus, the remained 58-72% of the energy input is transformed to thermal losses or waste heats and dumped into the environment as thermal pollution.

The purpose of the study is to assess the waste heat potential of the biogas engine power plants in Thai POMs. This assessment will be presented by using secondary data of a selected Thai palm oil mill (POM) as a case study. The study is useful for the country's energy efficiency program (EEP 2015), and another benefit is to encourage the Thai POMs competitiveness.

II. METHODOLOGY AND THE SCOPE OF STUDY

The study was carried out through a selected palm oil mill which is suitable for the selection, namely it is a standard POM (45 tons per hour FFB and wet processing mill) and the POME has used to produce biogas as fuel in an engine power plant. The collected secondary data for a year, site survey, and observation were performed. The collected data analysis and calculations are carried out. The engine thermal balance at the actual running condition was calculated by using the engine manufacturer's data as base. These obtained data are used as the baselines to determine the waste heat potential of the engine power plants in Thai POMs.

The scope of study was created as shown in Fig. 1, and they are:

- to determine the average ratios of various output per ton FFB.
- to determine an electrical efficiency of the engine power plant.
- to determine a percentage of wet and dry processing mills of Thai POMs.
- to determine a status of the biogas engine based power plants in Thai POMs.
- to assess the waste heat potential of the engine based power plants in Thai POMs.

The following assumptions are used for the calculations:

- biogas lower heating value (LHV) is 5.833 kWh/Nm3 (based on 62% CH_4, 15.6 ℃, 101.2 kPa).
- palm fiber (PF) LHV is 3.278 kWh/kg.
- the engine power plant is steady running at 1,000 kW (as per VSPP regulation).
- boiler efficiency is 73 % (LHV) [18].
- the principal of energy conservation is used for the energy analysis.

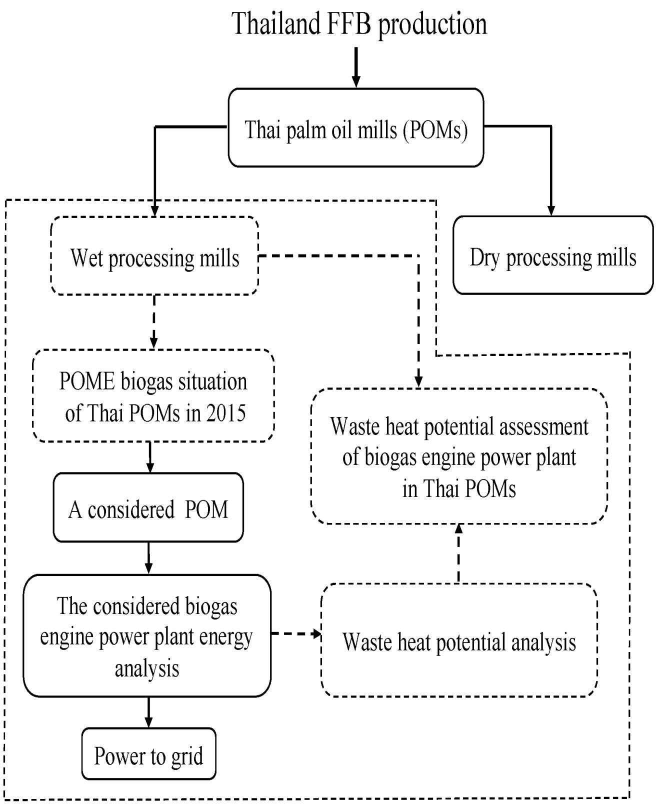

Fig. 1. Diagram of the methodology.

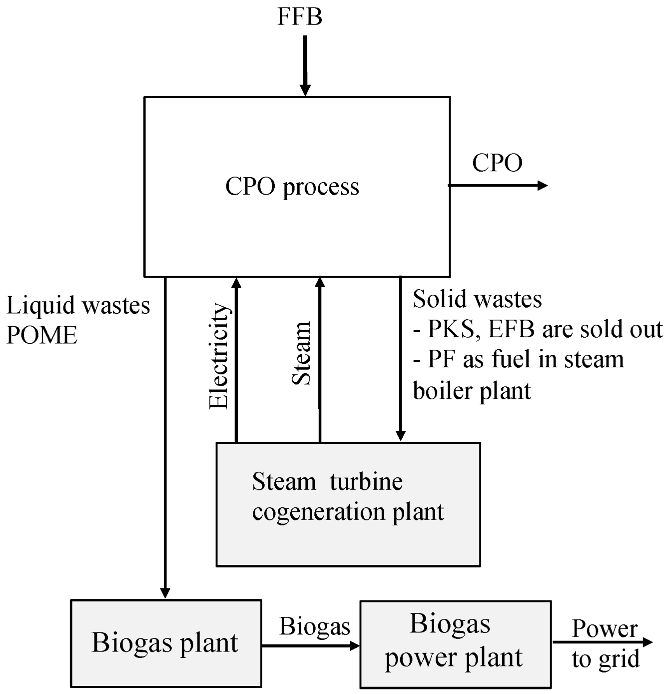

Fig. 2. The considered POM process diagram.

III. Results and Discussion

A. *Characteristics of biogas generation and engine power plant of the POM*

The typical schematic diagram of the selected POM is shown in Fig. 2. The POM consists of four main sections: a CPO process, a steam turbine cogeneration plant, a biogas plant and a biogas power plant.

The production capacity of the factory is 45 tons FFB per hour and operated with the wet process. The CPO is a primary product from the FFB extraction, but enormous by-products or biowaste, both solid and liquid are generated during the oil extraction. The solid biowaste, particularly PF is used as fuel in the boiler plant to produce steam and electricity using in the mill, while the PKS and EFB are sold out for other purposes. Whereas the liquid biowaste, POME is used to produce the biogas, it is used as fuel in the engine power plant. Table I shows the recorded yearly production data in 2011. According to the data, 200,805 tons of FFB are consumed, and 2,976,705 Nm^3 of biogas is produced from the POME. The generated biogas is used as fuel for the power generation in the engine power plant. Total electricity is generated 6.682 GWh and sold to the national grid under RE scheme of the country. Since the actual running of the engine is 1000 kW, the fuel flow rate can be calculated from

$$\dot{v}_{fuel} = \frac{BG_{prod}}{EE_{prod}} * EAR \qquad (1)$$

where $\dot{v}_{fuel}$ is fuel volumetric flow rate (Nm^3/hour), BG_{pro} (Nm^3) is biogas produced or consumed, EE_{prod} is electrical produced (kWh), and EAR is the power output of the engine actually running (kW). The calculated fuel flow rate is shown

TABLE I. THE RECORDED YEARLY PRODUCTION DATA OF THE CONSIDERED POM IN 2011

FFB consumed tons/year	POME produced m^3/year	Biogas produced Nm^3/year	Energy input kWh	Electrical generated kWh	Power output kW	Fuel flow rate Nm^3/hour
200805	86649	2976705	17363120	6681962	1000	445.48

in Table I. Therefore, the electrical efficiency of the engine power plant can be calculated by

$$\eta_{ele} = \frac{EAR}{\dot{Q}_{in}} * 100 = \frac{EAR}{\dot{v}_{fuel} * LHV_{fuel}} * 100 \quad (2)$$

where $\dot{Q}_{in}$ is energy input (kW), $\dot{v}_{fuel}$ is volumetric flow rate of biogas input (Nm^3/hour), and LHV_{fuel} is the lower heating value of the fuel (kWh/Nm^3). The LHV is selected due to water is normally in vapour state of the exhaust gas, thus the latent heat of water vapour condensation in the exhaust is not considered[15],[16].

The characteristics of the production ratios per ton FFB can be found from

$$POME_{pr} = \frac{POME_{pro}}{FFB_{cons}} \quad (3)$$

$$BG_{pr} = \frac{BG_{pro}}{FFB_{cons}} \quad (4)$$

$$PG_{pr} = \frac{EE_{pro}}{FFB_{cons}} \quad (5)$$

where $POME_{pr}$, BG_{pr} and PG_{pr} are production ratio of POME (m^3/ton FFB), biogas (Nm^3/ton FFB) and power (kWh/ton FFB) per ton FFB respectively, and $POME_{pro}$ is a production of the POME (m^3) and FFB_{cons} is the FFB consumed (ton).

Table II shows the results of POME, biogas and power production ratios per ton FFB. The POME production per ton FFB is 0.43 m^3, which is near the range of a previous study (044-1.18 m^3) [4], and the biogas is 14.82 Nm^3/ton FFB which is also in a range of other studies (12-19.6 m^3) [3], [19]. The biggest engine power generation per ton FFB is 33.28 kWh, which is a new figure of this field study. The electrical efficiency was calculated 38.48%. The electrical efficiency is slightly lower than the engine specification of 40%. The deviation depends on the feeding biogas quality variations and engine operating conditions.

B. *Energy analysis of the engine power plant*

At the engine power plant, a 1.063 MW engine is operated at 1000 kW output, which is 94% of FL. The fuel energy is fed into the spark-ignition (SI) engine where the combustion heat energy of the fuel is changed to mechanical work through a shaft which is connected to a generator where the mechanical work is converted to the electricity. Some heat from the combustion are lost to several portions: exhaust gas, cooling system, radiation, generator and other. The main heat losses of the SI engine are the engine exhaust and cooling system. Fig. 3 is shown an energy balance diagram of the engine power plant.

TABLE II. THE CALCULATED PRODUCTION RATIO OF POME, BIOGAS AND ELECTRICAL PER TON FFB

POME/FFB m^3/ton FFB	Biogas/FFB Nm^3/ton FFB	Electrical/FFB kWh/ton FFB
0.43	14.82	33.28

The energy balance of the engine power plant can be expressed as [17]

Total heat input = mechanical output + total heat losses (5)

where the total heat input is the fed fuel thermal energy, the mechanical output is a shaft power of the engine, and total heat losses are included: exhaust, cooling (LT and HT circuit), radiation and other balance heat. In this study, only the potential waste heat is considered, thus the other non-potential heat loss, such as radiation, generator and other are ignored. Therefore, the waste heat potential equation can be expressed as

$$\dot{Q}_{WHP,100\%} = \dot{Q}_{exh,487°C,100\%} + \dot{Q}_{LT,100\%} + \dot{Q}_{HT,100\%} \quad (6)$$

where $\dot{Q}_{WHP}$ is the waste heat potential of the engine power plant (kW), and $\dot{Q}_{exh,487°C}$ is the waste heat capacity of exhaust at 487°C outlet (kW). As the engine is operated at 94% FL or called 94% utilization factor (UF) [15], thus the corrected waste heats are considered. Fortunately, the waste heat quantity of a loaded operation is percent of the engine full-load rating [17], so the corrected waste heat potential of the engine with 94% utilization factor can be calculated as

$$\dot{Q}_{exh,487°C,94\%} = \dot{Q}_{exh,487°C,100\%} * UF \quad (7)$$

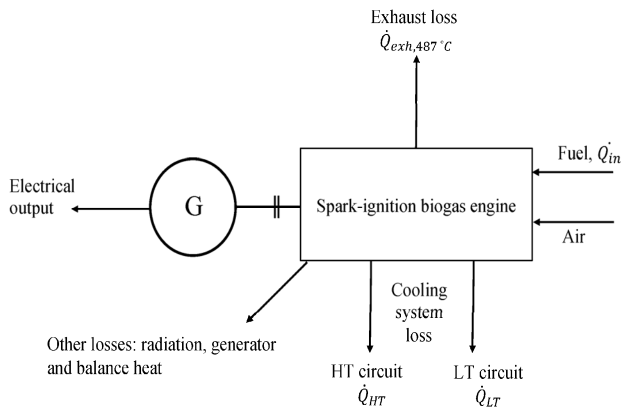

Fig. 3. The energy balance diagram of the biogas engine power plant.

$$\dot{Q}_{LT,94\%} = \dot{Q}_{LT,100\%} * UF \quad (8)$$

$$\dot{Q}_{HT,94\%} = \dot{Q}_{HT,100\%} * UF \quad (9)$$

where $\dot{Q}_{exh,487^{\circ}C,94\%}$, $\dot{Q}_{LT,94\%}$ and $\dot{Q}_{LT,94\%}$ are waste heat of 487˚C exhaust, LT and HT circuit at 94% of FL respectively. In this study, the exhaust waste heat utilization was designed at 180˚C of the heat exchangers outlet temperature. The designed temperature is to avoid the dew point temperature of sulfuric acid (130˚C) which is caused of a chemical corrosion. Thus, the exhaust waste heat potential can be calculated same as the method in (7), that is

$$\dot{Q}_{exh,487-180^{\circ}C,94\%} = \dot{Q}_{exh,487-180^{\circ}C,100\%} * UF \quad (10)$$

where $\dot{Q}_{exh,487-180^{\circ}C,94\%}$ is waste heat capacity of the exhaust which is cooled from 487˚C to 180˚C at 94% of FL. The LT and HT circuit waste heat are same as (8) and (9). Thus the total waste heat potential of the engine power plant can be expressed as

$$\dot{Q}_{WHP,94\%} = \dot{Q}_{exh,487^{\circ}C-180^{\circ}C,94\%} + \dot{Q}_{LT,94\%} + \dot{Q}_{HT,94\%} \quad (11)$$

where $\dot{Q}_{WHP}$ is the total waste heat potential of the engine (kW), and if the heat exchanger efficiency or called effectiveness factor (∈) is assumed as 0.85, thus the waste heat recoverable of the engine can be determined from

$$\dot{Q}_{WHR,94\%} = (\dot{Q}_{exh,487-180C,94\%} + \dot{Q}_{LT,94\%} + \dot{Q}_{HT,94\%}) * \varepsilon \quad (12)$$

where $\dot{Q}_{WHR}$ is waste heat recoverable (kW) from the engine and ε is an effectiveness factor of the heat exchangers.

Table III shows the calculated energy balance of the 1.063 MW engine power plant which is operated at 1,000 kW output in an hour (94% of FL). The waste heat potential in an hour was calculated 1,151 kW, or about 44.31% of the energy input; they are 516 kW and 635 kW of exhaust and cooling system respectively or 19.86% and 24.45% of energy feeding respectively. The total waste heat recoverable is 978.77 kW or 37.67% of the fuel energy.

C. Status of the engine based power plants in Thai POMs

Thailand had 200 POMs in 2015; they were 89 and 111 wet and dry processing mills respectively [20]. The whole installed capacity was 5,118 tons FFB per hour, and solely wet POMs are 4,655 tons FFB per hour or 91% of the total as shown in Fig. 4. In these wet processing mills, 69 factories or 77.5% have cooperated with the Thai Biogas project to generate biogas from the POME. It is estimated about 154.8 million Nm^3 biogas is generated, and about 93% or 144.4 million Nm^3 is used as fuel in the engine power plants while another 7% or 10 million Nm^3 used for heating processes. In these factories, 41 engine power plants have completed the COD (commercial operation date) with 324.5 GWh are generated and connected to the grid as shown in Fig. 5.

D. Capability of actual power generation and waste heat potential of the engine power plants in Thai POMs

In 2015, Thailand had produced about 11.015 million tons FFB and supplied to Thai POMs, while about 10.024 million tons or 91% is fed to the wet processing mills as described in 3.3 above. Thus, the total waste heat potential and recoverable of whole Thai palm oil mills can be determined from

$$WHP_{TH,POM} = WHP_r * LHV_{fuel} * BG_{pr} * FFB_{WPOM} \quad (13)$$

TABLE III. THE CALCULATED ENERGY BALANCE OF THE 1.063 MW ENGINE POWER PLANT AT 94% LOADED (1000 KW)

		Engine's data*		**Calculated data**		**Calculated waste heat capacity**			
		100% (full load)		**94% (actual run)**		**Potential**		**Recoverable****	
	Units		**% of Q_{in}**		**% of Q_{in}**		**% of Q_{in}**	**-**	**% of Q_{in}**
Energy input	kW	2658	100	2,599 [a]	100	-		-	
Fuel flow rate	Nm^3/hr.	443	-	445.48 [b]	-	-		-	
Electrical output	kW	1063	40.0	1,000	38.48	-		-	
Electrical efficiency	%	40	40	38.48		-		-	
Total engine cooling loss	kW	676	25.43	635 [c]	24.45	**635**		**540.12**	
HT circuit heat	kW	617	23.21	580 [c]	22.32	580	**44.31**	492.98	**37.67**
- Intercoolers 1st stage, Lube oil and Jacket	-	-	-	-	-	-		-	
LT circuit heat,	kW	59	2.22	55 [c]	2.71	55		47.14	
- Intercoolers 2nd stage	-	-	-	-	-	-		-	
Total exhaust gas loss at 487 °C	kW	811	30.51	762 [c]	37.24	-		-	
Exhaust gas loss at 487 °C to 180 °C	kW	549	20.65	516 [c]	19.86	**516**		**438.65**	

*Basis for exhaust gas data: natural gas 100% Ch_4; biogas 60% CH_4, 35% CO_2, and +/- 8% tolerance on thermal output.

**The waste heat recoverable is waste heat potential multiplied with the effectiveness, where effectiveness is 0.85.

[a] Energy input is calculated from fuel flow rate*LHV of biogas

[b] The data is taken from Table I.

[c] The data are calculated by heat at 100% multiply with 0.94 (94% utilization factor).

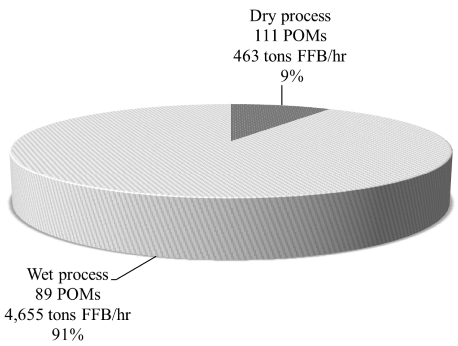

Fig. 4. The percentage of wet and dry processing mills in Thai POMs.

$$WHR_{TH,POM} = WHP_{TH,POM} * \varepsilon \quad (14)$$

where $WHP_{TH,POM}$ and $WHR_{TH,POM}$ is the whole waste heat potential and recoverable (GWh) of the whole Thai POMs, FFB_{WPOM} is the total FFB production of Thailand (million tons) which is fed to wet POMs, and WHP_r is a waste heat potential ratio (percent), which is determined from

$$WHP_r = \frac{\dot{Q}_{WHP,94\%}}{\dot{Q}_{in,94\%}} \quad (15)$$

The waste heat recoverable utilization can save biomass-fuelled, thus the fuel (palm fiber) saving equivalent of whole Thai POMs can be calculated from

$$FS = \frac{WHR_{TH,POM}}{(FB_{LHV} * \eta_b)} * 10^3 \quad (16)$$

where FS is the whole fuel saving in a year (ton), FB_{LHV} is a lower heating value of the palm fiber (kWh/kg), and η_b is the boiler efficiency.

The Table IV shows the results of the waste heat potential of the engine based power plant in Thai POMs. The total waste heat potential and recoverable were calculated 384.11 and 326.49 GWh, which are 44.31% and 37.67% of the fuel energy respectively, or equivalent saving about 136,440 tons a year of palm fiber. The capability of the power generation was calculated 333.57 GW, while 324.5 GWh had connected to the grid as shown in Fig. 6. It means that 97% of the biogas power generation has connected to the national grid.

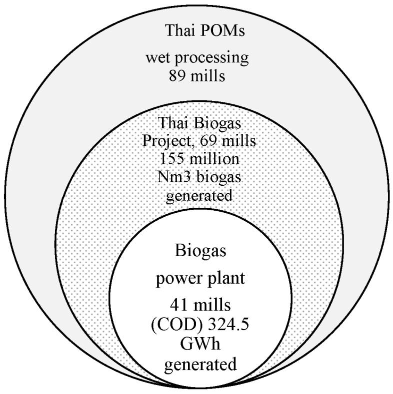

Fig. 5. Status of the biogas engine power plants in Thai POMs.

TABLE IV. THE WASTE HEAT POTENTIAL AND RECOVERABLE OF THE ENGINE POWER PLANTS IN THAI POMS

Items	Factor	Unit	Total	Unit
FFB production[a]	0.91	x 10^6 Ton	10.024	x 10^6 Ton
POME production[b]	0.43	m^3/ton FFB	4.33	x 10^6 m^3
Biogas production[c]	14.82	Nm^3/ton FFB	148.60	x 10^6 Nm^3
Energy input[d]	5.833	GWh/10^6 Nm^3 (biogas)	866.79	GWh
Power production[e]	38.48	% of energy input	333.57	GWh
Waste heat potential[f]	44.31	% of energy input	384.11	GWh
Recoverable waste heat[g]	37.67	% of energy input	326.49	GWh
Biomass saving (palm fiber)[h]	417.90	ton/GWh (heat recoverable)	136440	tons

[a] The factor is based on 91% of total FFB production (11,015,872 tonnes) in 2015 fed in wet process mills.
[b] The factor is taken from an average ratio in Table 2.
[c] The factor is taken from an average ratio in Table 2.
[d] The factor is used biogas LHV 5.833 kWh/Nm^3
[e] The factor is used electrical efficiency from Table 1.
[f] The factor is taken from Table 3.
[g] The factor is percentages combination of exhaust loss at 180 °C and total cooling loss in Table 3.
[h] The factor is calculated by 1000/(LHV palm fiber*boiler eff.)
where : the palm fibre LHV and boiler efficiency are 3.278 kWh/kg and 0.73 respectively.

IV. CONCLUSIONS

In the last decade, the biogas from Thai POME has been used as fuel in the engine based power plants supporting the country's RE scheme without consideration the engine waste heat utilization. This study demonstrates the enormous waste heat of the engine based power plants in Thai POMs had a high potential, thus utilization of the waste heat for other purposes is sustainability. Further study is to utilize the waste heat to produce steam or hot water in a cogeneration model, thus supporting the energy efficiency scheme of the country.

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