2016 International Conference on Sustainable Energy Engineering and Application (ICSEEA)

Potential of the Engine-Driven Cogeneration System in a Palm Oil Mill in Thailand

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Abstract—**Biogas engine based power plants in Thai palm oil mills (POMs) plays a crucial role in the renewable energy policy of the country. Thermal efficiencies of the engine power plants range from 25-44%, while more 60% of the feeding energy is converted to waste heats, which mainly are engine cooling and exhaust. Recovering and utilizing such waste heat improves the energy efficiency. The objective of this study was to investigate the potential and feasibility of a cogeneration driven by the waste heat of the engine power plant in Thai POMs. A case study approach was conducted, and secondary data of the mill were collected and used as baselines for the calculation. The cogeneration model and techno-economic feasibility were presented. It shows that the thermal efficiency of the cogeneration has increased from 37.34% to 75.60% compared with the conventional approach. Steam and hot water production from the waste heat of 1 MW engine are 659 kg/hour and 8.54 m^3/hour respectively. Thus, saving the boiler biomass-fuelled of the mill about 2,748 tons a year with a simple payback is 1.3 years. These data demonstrate the engine-driven cogeneration system is a co-benefits way for the energy efficiency improvement of Thai POMs, and it should be implemented nationwide.**

Keywords— ***cogeneration; engine power plant; palm oil mill; biogas; waste heat recovery***

I. INTRODUCTION

The oil palm is a major oil crop of the world. It is significantly involved both economic and energy sector. The main product of palm oil industry is crude palm oil (CPO) while huge bio-waste typical palm fiber (PF), empty fruit bunch (EFB), palm kernel shell (PKS) and palm oil mill effluent (POME) are generated and used as renewable energy (RE) resource [1]. The world's largest CPO producers are Indonesia, Malaysia, and Thailand respectively. In 2015, fresh fruit bunch (FFB) 11.02 million tons are produced and fed to Thai palm oil mills (POMs) [2]. Thus, annually, the enormous bio-waste both robust and liquid are generated and identified as the RE resource of the country. The palm fiber is primary used as fuel in boilers to produce steam and power in steam turbine power plants, while palm kernel shell (PKS) and empty fruit bunch (EFB) are sold out for several applications. Meanwhile, liquid bio-waste, palm oil mill effluent (POME) is mainly used to produce biogas and used as fuel in the engine power plants. In 2015, about 89 POMs in Thailand had generated 155 million Nm^3 of biogas from the POME, and 93% of the produced biogas is used as fuel in engine power plants generating the electricity, thus supporting the country's RE policy. The engine thermal efficiency may range from 25 to 44% [3], and another 56-75% of the feeding energy is transferred to waste heats mainly the exhaust and cooling system which dumped into the environment. Thus, utilizing the waste heat for other purposes with a cogeneration model is sustainable. Cogeneration or combined heat and power (CHP) is a simultaneous production of electricity and heat from a single fuel source. Many studies of the waste heat utilization in cogeneration models have been published in several publications [4]-[8], and this technology has been proven for over 100 years [9]. The cogeneration is most suitable and profitable, if thermal load matches or larger than the heat output of the co-generator [10]. Since, the POMs processing requires much thermal load both steam and hot water, utilizing these waste heats of the engine-generators to produce extra steam and hot water in the cogeneration model is a very challenging strategy of Thai POMs. Therefore, the proposed engine-driven cogeneration system in Thai POMs is an essential to achieve a co-benefit in energy efficiency and environmental improvement.

The study investigates the potential and feasibility of the engine-driven cogeneration system in Thai POMs, and it will be presented by implementing a selected POM in Thailand as a case study approach. The study is useful for either Thai POMs or cluster engine power plants who plan to utilize the engine waste heat. And it is responding to the energy efficiency program of the country.

II. METHODOLOGY AND SCOPE OF STUDY

This study was performed with three main stages: a palm oil mill selection as a case study, secondary data collection, and data analysis and calculations. Fig. 1 shows the diagram boundary of the study. The collected data were analyzed and calculated. The thermal balance of the engine at actual running condition was calculated from the engine manufacturer's data by using a linear interpolation method. These obtained data are used as the baseline and carried out to determine the waste heat potential of the engine power plant. A cogeneration system driven by the waste heat was proposed. The simple payback period method is used for the economic evaluation. The following assumptions are used for calculations:

- Lower heating value (LHV) of fuels: biogas and palm fiber (PF) are 5.833 kWh/Nm3 (based on 62% CH4, 15.6 °C, 101.2 kPa.) and 3.278 kWh/kg respectively.

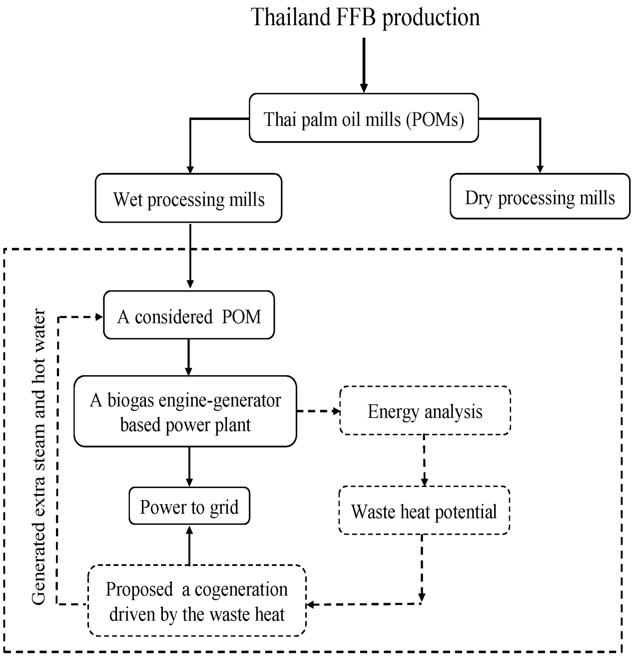

Fig. 1. A created diagram boundary of the study.

- The engine is constantly loaded at 1,000 kW, which is 94% of full load (FL).
- An average the boiler efficiency is 73 % (LHV) [11].
- The first law of thermodynamics is used for the energy analysis. Heat losses, kinetic and potential energy are negligible.
- Parasitic loads of the engine power plant and cogeneration plant: radiator fans, HT circuit cooling pump and ventilation fans are taken from the engine manufacturer, and otherwise by calculations.

III. SYSTEM ANALYSIS

A. *Plant description*

The mill is operated at 45 tons FFB per hour, and the FFB is consumed about 200,000 to 240,000 tons a year. The main processes are composed of a CPO process, a steam turbine cogeneration plant, a POME biogas plant and a biogas engine power plant. The FFB is fed to the CPO process for the crude palm oil production, meanwhile huge by-products: PF, EFB, PKS, and POME are generated. The PF is mainly used as fuel in the steam turbine cogeneration plant where electricity and steam are produced and used sufficiently in the factory. EFB and PKS are sold out to other applications, whereas the POME is treated for biogas production and used as fuel in the engine power plant as shown in the Fig .2. Table I shows the monthly collected data throughout the year 2011. The mill total operation hours is 4,552 hours with 200,805 tons FFB are fed

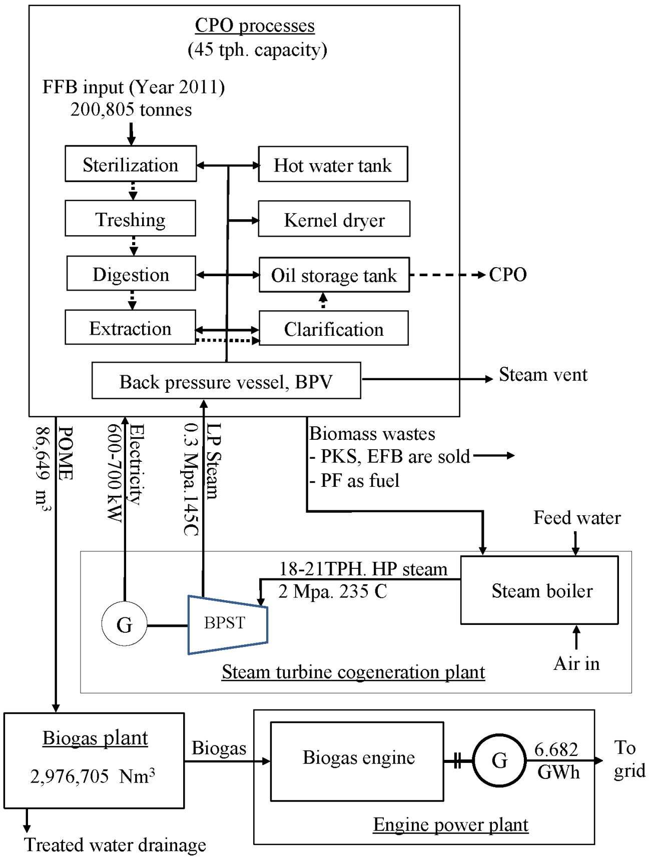

Fig. 2. Schematic diagram of the considered POM.

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

Month	FFB consumed (tons)	Capacity (ton/hr	Production (hr)	POME produced (m^3)	Biogas produced (Nm^3)	Energy input (kWh)[a]	Electrical produced (kWh)	Flow rate (Nm3/kWh)[b]
January	6,979	44	159	5,996	222,557	1,298,175	485,090	0.459
February	9,489	43	221	6,404	259,702	1,514,842	553,560	0.469
March	18,054	45	401	8,107	263,735	1,538,366	494,040	0.534
April	16,321	43	380	6,828	217,856	1,270,754	495,400	0.440
May	16,075	44	365	8,648	304,539	1,776,376	718,512	0.424
June	21,680	44	493	7,224	238,767	1,392,728	549,120	0.435
July	19,762	44	449	7,056	257,939	1,504,558	619,830	0.416
August	20,990	44	477	6,542	227,160	1,325,024	489,400	0.464
September	18,569	44	422	6,449	210,125	1,225,659	476,200	0.441
October	21,264	44	483	7,672	252,352	1,471,969	575,700	0.438
Novmber	18,217	45	405	7,747	230,168	1,342,570	547,310	0.421
December	13,405	45	298	7,976	291,805	1,702,099	677,800	0.431
Average	16,734	44	379	7,221	248,059	1,446,927	556,830	0.445
Total	200,805	-	4,552	86,649	2,976,705	17,363,120	6,681,962	-

[a] Energy input was calculated by the produced biogas multiplied with the biogas LHV, and biogas LHV is 5.833 kWh/Nm3 (Based on 62% CH_4 at 15.6 C, 101.32 kPa.)

[b] Flow rate is calculated by the produced biogas divided by electrical produced. In this study is 445 Nm^3/hr, where the electrical output is 1000 kW.

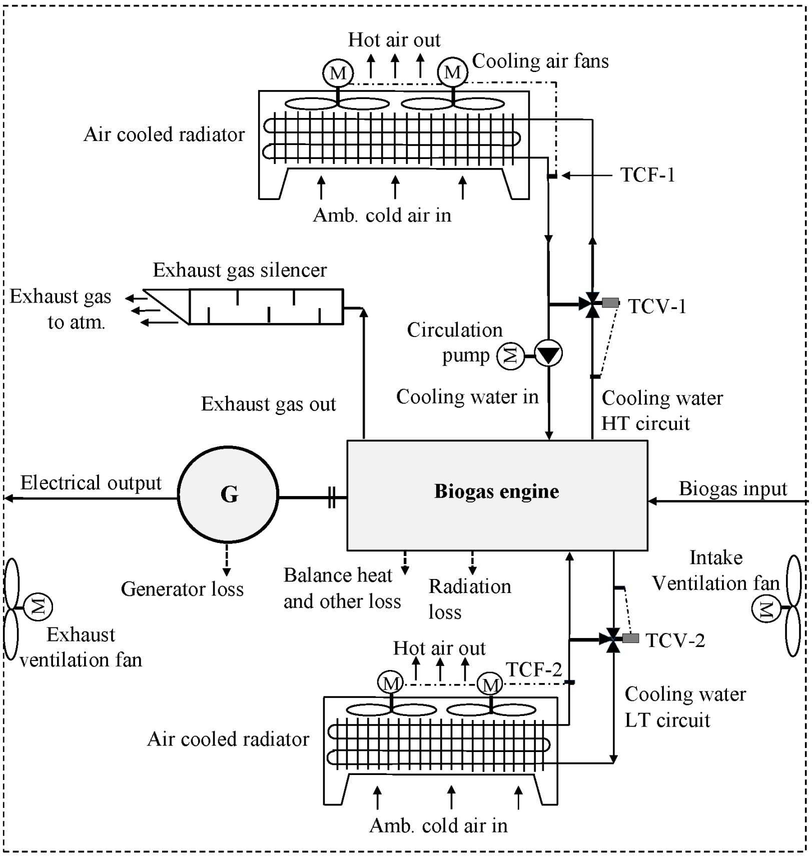

Fig. 3. The schematic diagram of biogas engine based power plant.

to the mill and generated 86,649 m^3 of POME, which is transformed to 2,976,705 Nm^3 biogas and used as fuel in the engine power plant producing 6.682 GWh to the grid.

B. *Energy analysis and proposed the engine-driven cogeneration system*

The engine is an SI engine, which its configuration is V 70°, 20 cylinders, 4-stroke, water cooled, 1500 RPM, 400 VAC, and 1063 kW rated. The engine is operated at 1000 kW output (94% of the rated or 94% utilization factor, UF). Fig. 3 is shown the schematic diagram of the engine power plant.

The biogas is fed into the engine where the chemical energy is transformed into electricity. During the combustion process in the engine, heat is transferred to the engine cooling system and exhaust as waste heats. The engine cooling system consists of two circuits: a low-temperature circuit (LT circuit) and a high-temperature circuit (HT circuit). The LT circuit receives the heat from the 2nd stage intercooler, whereas the HT circuit receives the heat from cylinder jacket, lubrication system and 1st stage intercooler (also called jacket cooling). The cooling water temperature of LT and HT circuit are controlled in the range 50-52.3°C and 70-90°C respectively, and these circuits are a closed system. Each circuit is separately operated by an individual circulation pump. The LT circuit is operated by a pump driven by mechanical in the engine block, whereas the HT circuit is operated by an electric pump externally. These pumps convey the cooling water to air cooled radiators where the heat is extracted. And to maintain the LT and HT circuit temperature within the range, so either temperature controller of cooling fans: TCF-1 and TCF-2 or automatic temperature control valves: TCV-1 and TCV-2 are cooperated for the engine safety. Meanwhile, another main waste heat, exhaust gas is escaped to the environment through a silencer, and other minor energy losses such as surface radiation, generator loss, and other balance are unavoidable and dissipated. Thus, utilizing the potential waste heat from the cogeneration system is proposed. The proposed engine-driven cogeneration system is shown in Fig. 4.

In this study, the high-temperature waste heat from the exhaust was designed to generate steam at 0.5 MPa and saturated temperature, and heat recovery steam generator (HRSG) is used. Whereas, the waste heat from the engine cooling system (LT and HT circuit) was designed to produce hot water from 30 to 85 , and plate heat exchangers (PHE) are used.

For the steam generation, the engine exhaust temperature is 487˚C; it is passed through a TCD (temperature control damper) and the HRSG where the steam generation is acted. The HRSG gas outlet temperature was designed at 180˚C above the sulfuric acid dew point (130˚C) to avoid the chemical corrosion [12]. The TCD is automatically worked to vent the exhaust to the atmosphere for safety purpose. The feed water temperature outlet is designed 85˚C. The feed water system is controlled by the LC (level controller) and the feed water pump (FWP). For the hot water generation, the waste heat of the LT and HT circuit were designed to exchange the heat with the cold water inlet at PHE_{LT} and PHE_{HT} respectively. These PHEs are installed in series. Since the engine is operated in steady, thus the mass flow rate of the feed water is constantly designed. The first law of thermodynamics or principle of the energy conservation with a steady-state open system or steady state steady flow system is used for the energy analysis [13]. And if the kinetic energy, potential energy, and heat loss are negligible, the steady flow equation of single inlet and exit can be written as

$$\dot{Q} + \dot{W} = \dot{m}(h_2 - h_1) = \dot{m} * Cp * (T_2 - T_1) \qquad (1)$$

where $\dot{Q}$ and $\dot{W}$ are net input of heat and work, $\dot{m}$ is mass flow rate of fluid, h_1, h_2 are inlet and exit enthalpy of fluid respectively, C_p is a specific heat at constant pressure of fluid, and T_1, T_2 are inlet and exit temperature of fluid respectively.

In this study, the engine power plant was analyzed; thus the electrical efficiency of the engine is expressed as

$$\eta_{ele} = \frac{\dot{W}_{gen,out}}{\dot{Q}_{in}} = \frac{\dot{W}_{gen,out}}{\dot{v}_{fuel} * LHV_{fuel}} \qquad (2)$$

where $\dot{W}_{gen,out}$ is electrical power output of the engine (kW), $\dot{Q}_{in}$ is energy input (kW), $\dot{v}_{fuel}$ (Nm^3/hour) is the volumetric flow rate of the biogas, and LHV_{fuel} is the biogas lower heating value (kWh/Nm^3). The LHV is selected due to water is normally in vapor state of the exhaust; thus the latent heat of water vapor condensation in the exhaust is not considered [3], [14]. While the thermal efficiency of the engine power plant can be analyzed same as a gas power plant [13], thus the thermal efficiency of the engine power plant is

$$\eta_{th,PP} = \frac{\dot{W}_{net,PP}}{\dot{Q}_{in}} = \frac{\dot{W}_{net,PP}}{\dot{v}_{fuel} * LHV_{fuel}} \qquad (3)$$

where $\dot{W}_{net,PP}$ is the net power output of the engine power plant (kW). In this power plant, some devices called parasitic loads are needed to run the system. So, the net power output can be modified as

$$\begin{aligned} \dot{W}_{net,PP} &= \dot{W}_{gen,out} - \dot{W}_{parasit,PP} \\ &= \dot{W}_{gen,out} - [\dot{W}_{cwp,HT} + \dot{W}_{rf} + \dot{W}_{vf}] \qquad (4) \end{aligned}$$

where $\dot{W}_{parasit,pp}$ are parasitic loads of the power plant (kW), which are comprised of $\dot{W}_{cwp,HT}$, $\dot{W}_{rf}$ and $\dot{W}_{vf}$, where $\dot{W}_{cwp,HT}$ is a load of the HT circuit pump, $\dot{W}_{rf}$ is a load of radiator fans and $\dot{W}_{vf}$ is load of ventilation fans. These load

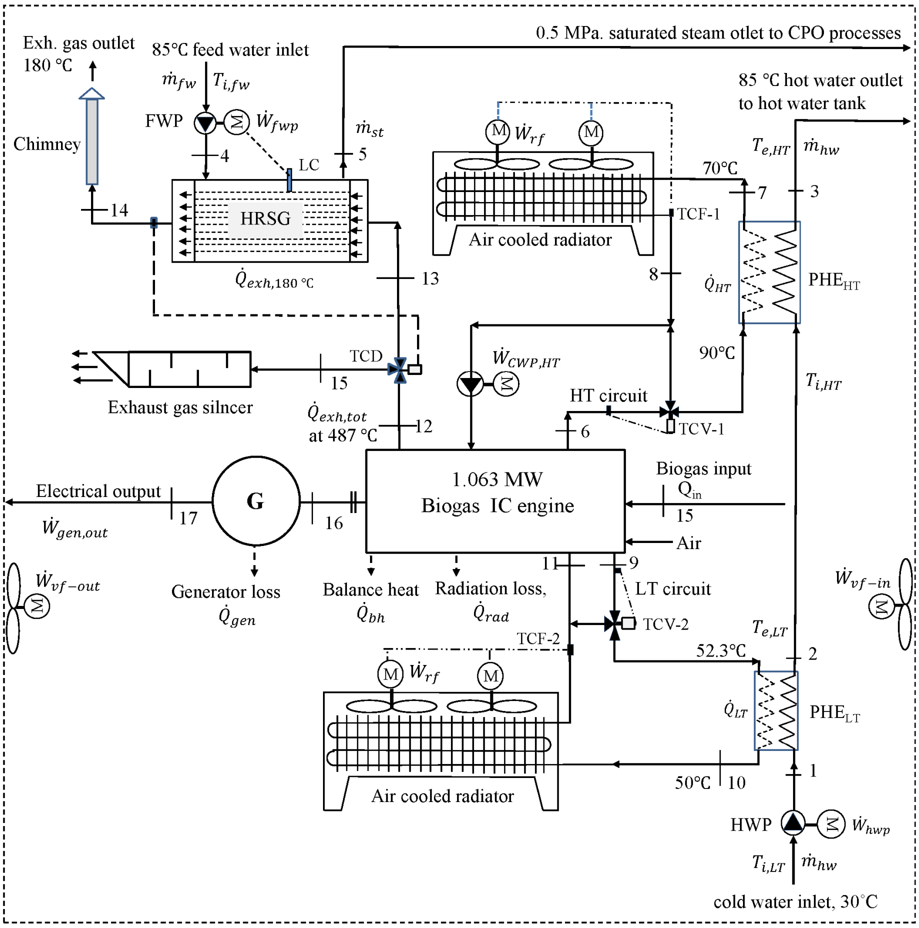

Fig. 4. The proposed 1.063 MW engine-driven cogeneration.

figures are taken from the engine manufacturer. In addition, the simple energy balance of the engine power plant may be written as [15]

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

where total heat input is the combustion heat of fuel, mechanical output is the engine shaft power, and total thermal output or heat losses are composed of exhaust, cooling (LT and HT circuit), radiation and other balance heat. As the engine shaft power is used to drive a generator to convert the mechanical to electricity, thus the generator loss is considered. Therefore, the (5) can be rearranged and written as

$$\dot{Q}_{in} = \dot{W}_{mech} + \dot{Q}_{L,tot} = \left(\dot{W}_{gen,out} + \dot{Q}_{gen}\right) + (\dot{Q}_{exh,487\,^{\circ}\mathrm{C}} + \dot{Q}_{LT} + \dot{Q}_{HT} + \dot{Q}_{rad} + \dot{Q}_{bh}) \quad (6)$$

where $\dot{W}_{mech}$ is the mechanical output (kW) and $\dot{Q}_{L,tot}$ is total heat losses (kW). $\dot{W}_{gen,out}$ is the generator output, $\dot{Q}_{gen}$ is the generator loss, $\dot{Q}_{exh,487\,^{\circ}\mathrm{C}}$ is the exhaust heat loss at 487 ℃, $\dot{Q}_{LT}$ is LT circuit heat loss at loaded, $\dot{Q}_{HT}$ is HT circuit heat loss at loaded, $\dot{Q}_{rad}$ is radiation loss and $\dot{Q}_{bh}$ is other balance heat. As the waste heat quantity of a loaded operation is percent of the engine full-load rating [15], the considered waste heat of the engine based power plant at 94% of full load (FL) can be determined by the linear interpolation method as follows

$$\dot{Q}_{exh,487^{\circ}C,94\%} = EH_1 - (EH_1 - EH_2) * (\frac{D_6}{D_{25}}) \quad (7)$$

$$\dot{Q}_{LT,94\%} = LT_1 - (LT_1 - LT_2) * (\frac{D_6}{D_{25}}) \quad (8)$$

$$\dot{Q}_{HT,94\%} = HT_1 - (HT_1 - HT_2) * (\frac{D_6}{D_{25}}) \quad (9)$$

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 the engine FL respectively, and EH_1, EH_2, LT_1, LT_2, HT_1 and HT_2 are waste heat of the exhaust, LT and HT circuit at 100% and 75% of the engine FL at same condition, which are given by the engine manufacturer, and D_6 and D_{25} are percent different from 100 and 75, and 100 and 94 respectively, which are 6 and 25 (percent) for D2 and D25 respectively. In this study, the exhaust waste heat is assumed to utilize until the exhaust temperature is reduced from 487˚C to 180˚C at the heat exchangers outlet. The exhaust outlet temperature was designed at 180 ˚C to avoid the chemical corrosion of the sulfuric acid which had a dew point 130˚C. Thus, the exhaust waste heat potential can be expressed as

$$\dot{Q}_{exh,487-180^{\circ}C,94\%} = EH_1 - (EH_1 - EH_2) * (\frac{D_6}{D_{25}}) \quad (10)$$

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

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

where $\dot{Q}_{WHP}$ is the total waste heat potential of the engine (kW). Nevertheless, the waste heat utilization is prohibited 100% [15], and it depends on the heat exchanger efficiency or called effectiveness factor (∈). Thus the waste heat recoverable can be determined from

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

where $\dot{Q}_{WHR}$ is the total waste heat recoverable (kW) in an hour from the engine and ε is an effectiveness factor of the heat exchangers, which is assumed 0.85. In this paper, the engine–driven cogeneration system was offered to produce the steam and hot water, thus the cogeneration efficiency is a ratio of combination of a net power output and the waste heat recoverable divided by fuel energy input. That is,

$$\eta_{th,cogen} = \frac{\dot{W}_{net,cogen} + \dot{Q}_{WHR}}{\dot{Q}_{in}} = \frac{\dot{W}_{net,cogen} + \dot{Q}_{WHR}}{\dot{v}_{fuel} * LHV_{fuel}} \quad (13)$$

where $\dot{W}_{net,cogen}$ is the net power output of the cogeneration plant (kW). Also, some parasitic loads are used in the cogeneration plant. Therefore, the net power outputs of the cogeneration are

$$\dot{W}_{net,cogen} = \dot{W}_{gen,out} - \dot{W}_{parasit,cogen} \quad (14)$$

$$\dot{W}_{net,cogen} = \dot{W}_{gen,out} - [\dot{W}_{cwp,HT} + \dot{W}_{hwp} + \dot{W}_{fwp} + \dot{W}_{vf} \quad (15)$$

where $\dot{W}_{parasit,cogen}$ are parasitic loads in the cogeneration plant (kW), and composed of $\dot{W}_{cwp,HT}$, $\dot{W}_{hwp}$, $\dot{W}_{fwp}$ and $\dot{W}_{vf}$ which are loads of HT circuit cooling pump, hot water pump, HRSG feed water pump and ventilation fans respectively. The HT circuit cooling pump and ventilation fan loads find from the engine data, and other parasitic loads can be calculated from

$$\dot{W}_{hwp} = \frac{\dot{m}_{hw} * g * H}{\eta_p} \quad (16)$$

$$\dot{W}_{fwp} = \frac{\dot{m}_{fw} * g * H}{\eta_p} \quad (17)$$

where $\dot{m}_{hw}$ and $\dot{m}_{fw}$ are mass flow rate of hot water and feed water of HRSG (kg/hr) respectively, whereas g, H and η_p are constantly national gravity (m/s^2), head of water (m.), and pump efficiency respectively. The waste heat capability can be represented by degrees and flow rates of the generated hot water and steam at constant flow. The Eq. (1) is used to determine these flow rates, and due to has no work output ($\dot{W} = 0$), the Eq. (1) is modified as

- for hot water generation

$$\dot{m}_{hw} = \frac{\dot{Q}_{LT} *\in}{Cp_{hw}(T_{e,LT} - T_{i,LT})} + \frac{\dot{Q}_{HT} *\in}{Cp_{hw}(T_{e,HT} - T_{e,LT})}$$

$$= \frac{(\dot{Q}_{LT} + \dot{Q}_{HT}) *\in}{Cp_{hw}(T_{e,HT} - T_{i,LT})} \quad (18)$$

- for steam generation

$$\dot{m}_{st} = \frac{\dot{Q}_{exh,180C} *\in}{h_{st} - h_{fw}} \quad (19)$$

where $\dot{m}_{hw}$ is a mass flow rate of the hot water (kg/hr), Cp_{hw} is a specific heat of hot water (kj/kg-˚c), $T_{i,LT}$, $T_{e,LT}$, $T_{i,HT}$ and $T_{e,HT}$ ($T_{e,LT}$ = $T_{i,HT}$ when the heat loss is negligible) are hot water inlet and outlet temperature (˚C) of PHE_{LT} and PHE_{HT} respectively, and $\dot{m}_{st}$ is a mass flow rate of the generated steam (kg/hr), h_{fw} is enthalpy of feed water (kj/kg) at HRSG inlet, h_{st} is enthalpy of saturated steam (kj/kg) at HRSG outlet. As the LT circuit temperature must be kept in the rang, the hot water outlet temperature at PHE_{LT} ($T_{e,LT}$) can be determined by

$$T_{e,LT} = T_{i,LT} + \frac{\dot{Q}_{LT}}{Cp_{hw} * \dot{m}_{hw}} \quad (20)$$

And the total running hours of the engine in a year can be estimated by

$$TER = \frac{TEP}{W_{gen,out}} \quad (21)$$

where TER is the total engine running hour (hours/year), TEG is the total electricity produced in a year (kWh) from Table I, and $W_{gen,out}$ is the engine power output (kW) at loaded (1000 kW). The generated steam and hot water from the waste heat can save the boiler fuel, and the saving is calculated from

$$FS = \frac{Q_{WHR} * TER}{(FB_{LHV} * \eta_b) * 1000} \quad (22)$$

where FS is the fuel saving (tons/year), FB_{LHV} is the lower heating value of palm fiber (kWh/kg), and η_b is the boiler efficiency. The saving from the proposed cogeneration system is profitable, and the revenue of the saving can be found from

$$AR_{FS} = FS * PF_{price} \quad (23)$$

where AR_{FS} is the annual revenue from the fuel saving, PF_{price} is the palm fiber price (baht/ton), thus the investment cost return can be calculated by

$$PB = \frac{TC_{inv}}{AR_{FB}} \quad (24)$$

where PB is the payback period of the investment (year), TC_{inv} is the total cost of cogeneration investment (Thai baht).

IV. RESULTS AND DISCUSSIONS

A. The efficiency and waste heat potential of the engine based power plant in the POM

Table II shows the waste heat potential and engine power plant efficiency, whereas Table III shows the results of the energy balance and losses of the engine power plant at 94% of FL. The electrical and power plant efficiency of the engine were calculated 38.48% and 37.34% respectively. The power plant efficiency is slightly lower than the electrical efficiency due to the parasitic loads were considered. The power plant parasitic loads are 1.14% of energy input or 3.89% of power output. The total waste heat of the engine was calculated 58.16% of feeding energy, while the waste heat potential is 44.56%, which is the exhaust and cooling system: 19.82% and 24.74% respectively. The specific fuel consumption (SFC) and electrical efficiency are slightly different from the engine specification which is 2.43 kWh/kWh and 40% respectively. These deviations depend on the fed biogas quality and engine operating conditions [16].

B. The proposed biogas engine-driven cogeneration system in the POM

Table IV shows the calculated energy balance of the engine-driven cogeneration, while Table V shows the results of the proposed engine-driven cogeneration, andFig. 5 shows the energy flow diagram of the 1.063 MW engine based cogeneration. The waste heat potential and recoverable of the engine per hour is 1,158 kW and 984.24 kW respectively. The produced steam and hot water from the waste heat in an hour were calculated 659 kg and 8.544 m^3 respectively. The cogeneration plant efficiency was calculated as much as 75.54%, this value is higher than the conventional approach as much as37.34%, which is increased by the engine waste heat utilization. The cogeneration parasitic loads were calculated 21.27 kW, which is 0.82% of the thermal power input or 2.13% of power output, which is almost same as the engine power plant due to the air-cooled radiator fans were stopped in cogeneration mode. The total engine running hour was calculated 6,682 hours, and the palm fiber saving was calculated 2,748 tons a year.

C. Economic evaluation

The proposed cogeneration system has saved 2,748 tons fuel a year. This saving can be evaluated the payback period of the investment, and the following assumptions were used:

1) The estimated investment costs are: the HRSG and PHE 3,000,000, piping and insulation system 1,000,000 Baht (estimated 100 meters), the existing exhaust gas ducting and cooling water piping modification 350,000 Baht, and the electrical system and others 300,000 Baht

2) Annual revenue from fuel saving is based on palm fiber price 1,300 Baht/ton [17]

The simple payback period was calculated 1.3 years. It is shown that the investment is feasible and attractive.

D. Technical barriers

The palm oil production is seasonal. An average production hour of the selected POM is 4,552 hours a year, while the engine running hour is 6,682 hours. Thus, another 2,130 hours of the generated extra steam and hot water from the cogeneration system must be managed effectively. A possible way is to use the extra steam for PKS drying during no CPO production, whereas the hot water may recirculate through the PHE of the LT and HT circuit to keep its temperature. And to maintain the engine performance, the system modification of the engine must be correctly designed.

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

		Engine manufacturer's data				**Calculated data**	
		100% (full load)		**75% (part load)**		**94% (loaded condition)**	
	Units		% of Q_{in}		% of Q_{in}		% of Q_{in}
Energy input, $\dot{Q}_{in}$	kW	2658	100	2047	100	2599[a]	100
Fuel flow rate	Nm^3/hr.	443	-	341	-	445[b]	-
Mech. Output, $\dot{W}_{mech}$	kW	1095	41.20	821	40.11	1029[c]	39.61
Electrical output, $\dot{W}_{gen,out}$	kW	1063	40.0	796	38.9	1000	38.48
Generator loss, $\dot{Q}_{gen}$	kW	32	1.20	25	1.22	29	1.13
Electrical efficiency, η_{ele}	%	40	40	-	38.9	38.48	38.48
Specific fuel consumption (SFC)	kWh/kWh	2.43	-	2.49	-	2.52	-
Total engine cooling Loss, $\dot{Q}_{CW,tot}$	kW	676	25.43	538	26.28	643[c]	24.74
HT circuit heat, $\dot{Q}_{HT}$	kW	617	23.21	499	24.38	589[c]	22.65
- Intercoolers 1st stage	kW	175	6.58	78	3.81	152[c]	5.84
- Lube oil	kW	118	4.44	100	4.89	114[c]	4.37
- Jacket	kW	324	12.19	321	15.68	323[c]	12.44
LT circuit heat, $\dot{Q}_{LT}$	kW	59	2.22	39	1.91	54[c]	2.09
- Intercoolers 2nd stage	kW	59	2.22	39	1.91	54	2.09
Total exhaust gas loss at loaded $\dot{Q}_{exh,487\,°C}$	kW	811	30.51	602	29.41	761[c]	29.28
Surface radiation, $\dot{Q}_{rad}$	kW	65	2.45	56	2.74	63[c]	2.42
Balance heat, $\dot{Q}_{bh}$	kW	11	0.41	30	1.47	16[c]	0.60
Error	kW	0	0.00	0	0.00	87	3.35
Total losses and error, $\dot{Q}_{L,tot}$	kW	1595	60.01	1251	61.11	1599	61.52
Exhaust gas loss at 180 C, $\dot{Q}_{exh,180°C}$	kW	549	20.65	408	19.91	515[c]	19.82
Parsitic loads, $\dot{W}_{parasit}$:	kW	29.60	1.11	-	-	29.60	1.14
- Air cooled radiator fans, $\dot{W}_{fan,rad}$	kW	10.00	0.38	-	-	10.00[d]	0.38
- HT circuit pump, $\dot{W}_{CWP,HT}$	kW	4.60	0.17	-	-	4.60[d]	0.18
- Ventilation fans, $\dot{W}_{vf}$	kW	15.00	0.56	-	-	15.00[d]	0.58

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

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

[b] The data is taken from table 1.

[c] The data are calculated by linear interpolation method.

[d] These parasitic loads are based on the engine manufacturer data

TABLE III. WASTE HEAT POTENTIAL AND ENGINE POWER PLANT EFFICIENCY

Energy losses	**Total waste heat**		**Waste heat potential**		**Power plant**
	kW	**% of input**	**kW**	**% of input**	**efficiency, %**
Exhaust gas*	761	29.28	515	19.82	37.34
Cooling water circuits	643	24.74	643	24.74	
Radiation	63	2.42	-	-	
Generator	29	1.13	-	-	
Balance heat	16	0.60	-	-	
Error	87	3.35	-	-	
Total	1599	61.52	1158	44.56	
Parasitic loads	29.60	1.14			

* Exhaust gas: the total waste heat and waste heat potential are based on exhaust temperature at 487 °C and 180 °C respectively

TABLE IV. THE CALCULATED ENERGY BALANCE AT 94% LOADED (1000 KW) OF THE 1.063 MW ENGINE BASED COGENERATION PLANT

Energy balance	**Units**		**% of Qin**
Energy input, $\dot{Q}_{in}$	kW	2599	100
Fuel flow	Nm^3/hr.	445	-
Mech. output, $\dot{W}_{mech}$	kW	1029	39.61
Electrical output, $\dot{W}_{gen,out}$	kWe	1000	38.48
Generator loss, $\dot{Q}_{gen}$	kW	29	1.13
Electrical efficiency, η_{ele}	%	38	38.48
Specific fuel consumption (SFC)	kWh/kWh	2.52	-
Total engine cooling loss, $\dot{Q}_{CW,tot}$	kW	643	24.74
HT circuit heat, $\dot{Q}_{HT}$	kW	589	22.65
- Intercoolers 1st stage (Engine jacket water cooling circuit)	kW	152	5.84
- Lube oil (Engine jacket water cooling circuit)	kW	114	4.37
- Jacket (Engine jacket water cooling circuit)	kW	323	12.44
LT circuit heat, $\dot{Q}_{LT}$	kW	54	2.09
- Intercoolers 2nd stage (Low temperature circuit)	kW	54	2.09
Total exhaust gas loss at 487 °C, $\dot{Q}_{exh,487\,°C}$	kW	761	29.28
Surface radiation, $\dot{Q}_{rad}$	kW	63	2.42
Balance heat, $\dot{Q}_{bh}$	kW	16	0.60
Error	kW	87	3.35
Total losses, $\dot{Q}_{L,tot}$	kW	1599	61.52
Exhaust gas loss at 180°C, $\dot{Q}_{exh,180°C}$	kW	515	19.82
Parasitic loads based cogeneration, $\dot{W}_{parasit}$:	kW	19.82	0.79
- Air cooled radiator fans, $\dot{W}_{fan,rad}$	kW	0	0.00
- HT circuit pump*, $\dot{W}_{CWP,HT}$	kW	5	0.18
- Ventilation fans*, $\dot{W}_{vf}$	kW	15	0.58
- Feed water pump of HRSG**, $\dot{W}_{fwp}$	kW	0.22	0.03
- Hot water pump**, $\dot{W}_{hwp}$	kW	1.45	0.23

* Parasitic loads are based on the engine manufacturer data

**Calculated parasitic loads are based on heads of feed water and HW pump: 70 and 35 m.WC, and efficiencies of pumps and motors are 75%.

TABLE V. THE CALCULATED ENERGY BALANCE AT 94% LOADED (1000 KW) OF THE 1.063 MW ENGINE BASED COGENERATION PLANT

Energy losses	**Waste heat potential**		**Effectiveness**	**Recoverable waste heat**		**Waste heat productions**		**Cogeneration**
	kW	**% of input**	**factor, ε**	**kW**	**% of input**	**steam, kg/hr**	**HW, m^3/hr**	**efficiency, %**
Exhaust gas	515	19.82	0.85	437.79	16.85	659	-	75.54
Cooling water circuits	643	24.74	0.85	546.45	21.03	-	8.544	
Radiation	63	2.42		-	-			
Generator	29	1.13		-	-			
Balance heat	16	0.60		-	-			
Error	87	3.35		-	-			
Total	1158	44.56		984.24	37.88			
Parasitic loads	21.27	0.82						

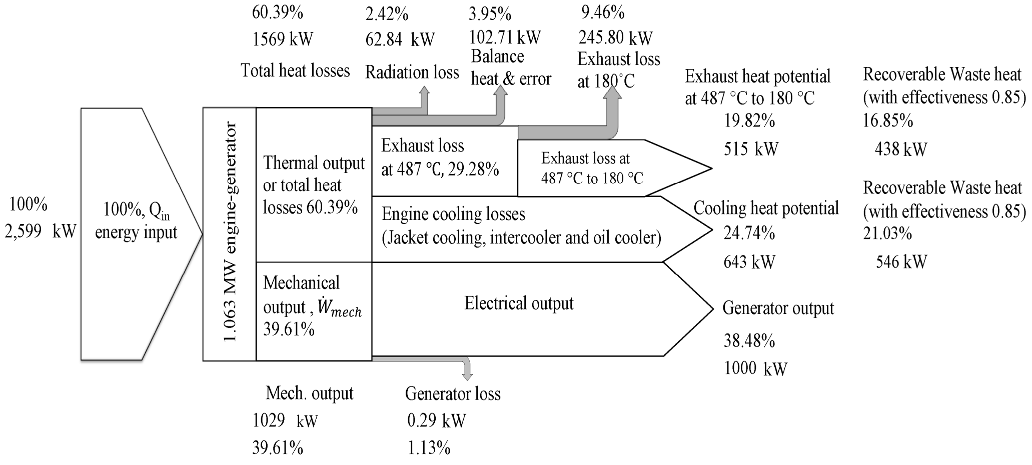

Fig. 5. The energy flow diagram of the 1.063 MW engine based cogeneration.

V. CONCLUSIONS

The study demonstrates that the engine-driven cogeneration system significantly increase the energy efficiency which means sustainability. The extra steam and hot water generation from the waste heat in the cogeneration model, technical barriers and economic evaluation were presented. Thus the proposed engine-driven cogeneration system of the POM should be implemented in the nationwide. Further study is to integrate the conventional steam turbine cogeneration and the proposed engine based cogeneration to increase the power generation in Thai POMs.

REFERENCES

[1] Sumiani Yusoff, Renewable energy from palm oil-innovation on effective utilization waste, Cleaner Production 2006;14:87-93.

[2] Agricultural statistics of Thailand 2015. Available from: http://www.oae.go.th/download/download_journal/yearbook55.pdf; (accessed May 2016)

[3] Kansim Zor. Gas engine based cogeneration and trigeneration plants, Fundamentals, grid synchronization, current legislation and environment effects, Lambert Academic publishing USA, 2015.

[4] M.S. Rocha, R. Andreos, J.R. Simões-Moreira, Performance tests of two small trigeneration pilot plants. Applied Thermal Engineering 2012;4:84-91

[5] António Domingues, Helder Santos, Mário Costa, Analysis of vehicle exhaust waste heat recovery potential using a Rankine cycle. Energy, 2013;49: 71-85

[6] Maogang He, Xinxin Zhang, Ke Zeng, Ke Gao, A combined thermodynamic cycle used for waste heat recovery of internal combustion engine. Energy 2011;36:6821-6829

[7] J. S. Jadhao, D. G. Thombare, Review on exhaust gas heat recovery for I.C. engine. International Journal of Engineering and Innovative Technology 2013;2 (12):93-100.

[8] Mahesh Shelar, V.K. Patil and G.N. Kulkarni, Engine Based Trigeneration with Thermal Storage, International Journal of Current Engineering and Technology, Special issue-2 (February 2014) 413-416

[9] Ibrahim Dincer, Marc A. Rosen, Exergy : Energy, Environment and Sustainable Development. 2nd ed. San Diego: Elsevier; 2013.

[10] Cecelio E. Gracias and lioyd S. Hoffstatter, Cogeneration systems analysis, in: F. William Payne, editor, Cogeneration management reference guide, Georgia: Fairmont

[11] Z. Husain, Z.A. Zainal, M.Z. Abdullah, Analysis of biomass-residue-based cogeneration system in palm oil mills, Biomass and Bioenergy 2003;24: 117-124

[12] V. Ganapathy. Industrial boilers and heat recovery steam generators: Design, Applications and Calculation. FL. USA : CRC Press, Taylor & Francis Group; 2003.

[13] Mehmet Kanoglu, Yunus A. Cengel and Ibrahim Dincer. Efficiency Evaluation of Energy. Lexington, KY, USA : Springer; 2015.

[14] Paul Breeze, Power generation Technologies, 2nd ed., Newnes is an imprint of Elsevier, CA, U.S.A., 2014

[15] Neil Petchers. Combined heating cooling & power hand book: Technologies and application, An integrated approach to energy resource optimization, The Fairmont Press, Inc., Georgia, 2003.

[16] National academy of sciences, Methane generation from human, animal and agricultural wastes. National academy sciences, New York, U.S.A., 2001.

[17] Kritsana Sommart and Suneerat Pipatmanomai, Assessment and imrovment of energy utilization in crude palm oil mill, 2011 International conferenceon chemistry and chemical process, IPCBEE 2011;10:161-166.