PROCESS OPTIMIZATION OF BIOMASS COMBUSTION OF AN INDUSTRIAL BOILER IN A PALM OIL MILL

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by

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As	Specific air flow rate (kg air/kg biomass)
C	Carbon mass fraction (%)
Ca	Ash content (%)
Cm	Moisture content (%)
H	Hydrogen mass fraction (%)
HHV_{EFB}	Higher heating value of EFB (MJ/kg)
HHV_f	Higher heating value of boiler's feed (MJ/kg)
HHV_{MF}	Higher heating value of MF (MJ/kg)
HHV_{PKS}	Higher heating value of PKS(MJ/kg)
N	Nitrogen mass fraction (%)
O	Oxygen mass fraction (%)
S	Sulfur mass fraction (%)
x_{EFB}	mass fraction of EFB in feed
x_{MF}	mass fraction of MF in feed
x_{PKS}	mass fraction of PKS in feed

LIST OF ABBREVIATIONS

EFB	Empty fruit bunch
FFB	Fresh fruit bunch
HHV	Higher heating value
LHV	Lower heating value
MC	Moisture content
MF	Mesocarp fibre
MPOB	Malaysia Palm Oil Board
NC	Non-conventional
POME	Palm oil mill effluent
PKS	Palm kernel shell

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PENGOPTIMUMAN PROSES DAN KAJIAN PADA PEMBAKARAN BIOMAS MENGGUNAKAN DANDANG PERINDUSTRIAN DI DALAM KILANG KELAPA SAWIT

ABSTRAK

Biojisim adalah salah satu tenaga yang boleh diperbaharui yang digunakan untuk menghasilkan kuasa elektrik. Kuasa elektrik dapat dijana menggunakan biomas melalui proses pembakaran di dalam dandang bertekanan tinggi. Tenaga daripada proses tersebut dipindahkan untuk menghasilkan wap air bertekanan tinggi yang akan menggerakkan turbin wap. Biomas kelapa sawit terutamanya janjang kosong (EFB), gentian mesocarp (MF), dan tempurung isirung (PKS) berpotensi tinggi untuk digunakan sebagai bahan bakar dandang tempatan. Hal ini kerana biojisim kelapa sawit merupakan antara biomas yang terbanyak terdapat di Malaysia. Walau bagaimanapun, nilai pemanasan daripada biomas mentah adalah rendah berbanding diesel. Kuasa yang dijana kurang daripada kuasa yang diperlukan menyebabkan keperluan untuk diesel sebagai bahan bakar tambahan. Oleh itu, pra-rawatan torefikasi pada biomas dapat meningkatkan ciri biomas lebih-lebih lagi EFB yang mempunyai kandungan lembap yang tinggi dan kandungan karbon yang rendah. Berdasarkan simulasi yang dijalankan menggunakan AspenPlus, campuran MF dan PKS dengan 5,820 kg/j sebagai bahan bakar kepada dandang hanya dapat menghasilkan 810 kWj elektrik berbanding 990 kWj elektrik yang diperlukan. Namun begitu, dengan bantuan torefikasi dan mengintegrasi EFB, dandang dapat menghasikan elektrik sehingga 940.917 kW yang mana jauh lebih tinggi berbanding kuasa yang dihasilkan biomas mentah. Melalui simulasi AspenPlus, kajian ini juga mendapati peningkatan suhu dandang dan kadar aliran udara secara diskret dapat meningkatkan penjanaan kuasa. Selain itu, pengurangan kadar aliran air pula dapat meningkatkan kuasa yang dijana. Akhirnya, pengoptimuman dalam mencapai nilai elektrik dapat dicapai dengan menaikkan

jumlah kadar aliran jisim bahan bakar biomas kepada 6,200 kg/j. Dengan hanya EFB sebagai bahan bakar dapat menjana 991.953 kWj manakala, campuran 50% EFB, 30% MF, dan 20% PKS menghasilkan 1005.805 kWj elektrik.

PROCESS OPTIMIZATION AND NUMERICAL STUDIES OF BIOMASS COMBUSTION OF AN INDUSTRIAL BOILER IN A PALM OIL MILL

ABSTRACT

Biomass is one of the major renewable energies used for production of power. Biomass generates power through combustion in a high-pressure environment. The energy from the process is transferred to produce high-pressure steam that will power up a steam turbine. Palm oil biomass especially empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS) has high potential to be utilized in local industrial boiler due to palm oil biomass is one of the most abundant biomasses available in Malaysia. However, the heating value from raw biomass is quite low compared to the conventional fuel which is diesel. This leads to insufficient power generation from biomass which requires addition of diesel to fulfil the electricity demand of the palm oil mill itself. Therefore, torrefaction is needed as pre-treatment to elevate the characteristics of the biomass especially EFB which exhibit high moisture content and low carbon content. Mixture of MF and PKS with 5,820 kg/h as feed in a boiler only produce 810 kWh of electricity compared to the electricity demand 990 kWh. However, by torrefaction of the biomass and addition of EFB, the electricity generated from the boiler can reach up to 940.917 kW which produce more power than the raw biomass. Additionally, increasing boiler temperature and air flow rate discretely increase the power generated. On the other hand, decreasing water flow rate increase the power generation. Finally, optimization to reach electricity demand by increasing the feed mass flow rate to 6,200 kg/h is achieved. 100% EFB alone able to produce 991.953 kWh while mixture of 50% EFB, 30% MF, and 20% PKS generates 1005.805 kWh of electricity.

CHAPTER 1

INTRODUCTION

1.1 Biomass

Biomass is generally defined as mass from living biological organisms which are animal, plant, and microorganisms. The main constituents for biomass are mostly lignocelluloses, fats, sugars, and proteins (Houghton, 2008). Biomass has its own versatility as it can produce wide range of products such as solid, liquid, gas, or even in the form of power. Biomass is also widely available all around the world and have storage and transportation flexibility (Nomiyama et al., 2014). Meanwhile, countries like United States of America (USA) and Japan established legal definition of biomass for certain reasons (“Definition of Biomass,” 2018). In USA, biomass refers to plant material from agricultural lands that are managed by means of harvesting, collecting, or as a waste material. Not only that, waste from animal, plant material from pastureland, food waste, and algae are also considered as biomass (“Definition of Biomass,” 2018). Besides, Number 1 in Article 1 of “Enforcement Ordinance on the Law Concerning Special Measures to Promote the Use of New Energy” in Japan cited that biomass main purpose is to be an energy sources by producing fuel from the material. Moreover, Number 2 in the same article specified that biomass is used “to gain heat” and Number 6 stated “to generate power” from biomass (Nomiyama et al., 2014).

It is well known that fossil fuels which includes coal and natural gas are rapidly depleting. The fossil fuels are considered as non-renewable energy however its usage keep increasing as the energy demand is also surging especially developing country like Malaysia (Mekhilef et al., 2011). Coal is also one of the major fuels used to generate global electricity. This electricity generation comes with a price of 10.1 Gt of carbon dioxide emission in 2018. It accounted for 30% of global carbon dioxide emission from energy generation (IEA, 2019). Not only that, toxic inorganic heavy metals are also released to the environment during extraction of the coal (Asadullah et al., 2014). Consequently, usage of coal as the main feedstock of combustion process is alarming as it is the leading root of global warming. Therefore, transition to usage of biomass feedstock in combustion process is necessary with the aim to reduce carbon cycle that influence the occurrence of global warming (Nomiyama et al., 2014).

On the other hand, current technology of biomass co-firing with coal is only allowed to be directly integrated as feedstock for 3-10% of coal plant capacity (Agbor et al., 2014). Meanwhile, even after pretreatment of biomass, it can be further substituted up to 40% of the feedstock (Khorshidi et al., 2014). There are several categories of biomass that can be obtained from various sources such as crops, industrial waste, and unutilized biomass parts from industry. This research is focused on the residual parts from the production of palm oil as the main source of biomass.

1.2 Palm oil mill biomass in Malaysia

To correlate, Malaysia has nearly 6 million hectare of palm tree plantation scattered all over Malaysia which responsible in producing over 100 million tons (Mt) of fresh fruit bunch (FFB) to be processed mainly for commercialization of palm oil. 22.87 Mt of empty fruit bunch (EFB), 14.03 Mt of mesocarp fibre (MF), and 5.72 Mt of palm kernel shell (PKS) are among the main biomass residual resulted from the 103.94 Mt processed in palm oil mill in 2017 (Sukiran et al., 2020).

Due to the huge amount of biomass residual produced, utilization of these biomass plays an important role in reducing the facility needed to handle it as a waste and simultaneously producing value-added products (Aljuboori, 2013). Firstly, MF is the pulp of the palm fruit which mainly used as biomass fuel. Meanwhile, PKS is the inner shell of the fruit which is known to produce premium activated carbon (Aljuboori, 2013). MF and PKS are the common feedstocks for the industrial boiler to generate steam for energy production because they are readily having low moisture content and high calorific value in raw material state (Mohd Faizal et al., 2018).

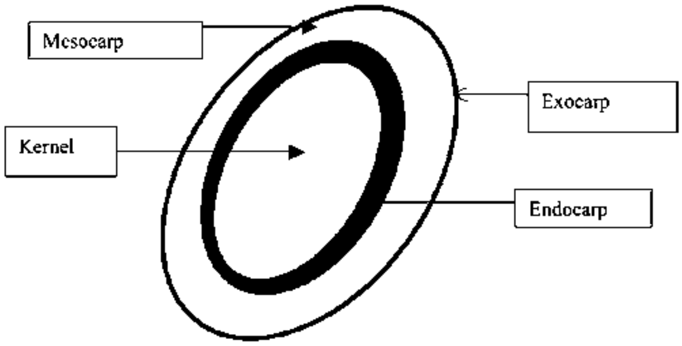

Figure 1.1 Fresh fruit bunch (Kwasi Poku, 2002)

EFBs on the other hand, the most generated biomass from palm oil mill, are usually used back in the plantation as mulch. Mulch serves to conserve moisture in soil, prevent growth of weed, and improve the quality of soil by covering the surface of soil around the palm tree (Sukiran et al., 2020). However, EFB able to generate around 3-fold profit by using it to produce bioenergy such as bioalcohol, solid fuel, and pulp (Aljuboori, 2013; Mubarak et al., 2016). EFB is considered as not suitable feedstock for combustion process as it has high moisture content, around 65% to 75% that lowers the calorific value and eventually affect the energy yield (Loh, 2017; Uemura et al., 2017). This is due to the moisture inside the EFB that need to be vaporized prior to the combustion process EFB (Loh, 2017).

1.3 Pre-treatment of biomass

Torrefaction is an example of the pre-treatment to the biomass in order to increase the efficiency of biomass during combustion process. Torrefaction is a thermochemical treatment that occurs around 200°C to 300°C under atmospheric pressure without presence of oxygen to prevent burning of biomass (van der Stelt et al., 2011). Exceeding the upper limit temperature would excessively devolatilize and carbonize the components as well as results in high lignin content loss in the biomass (Basu, 2018c). The treatment reduces the moisture content together with a part of high volatile organic component in the biomass (Asadullah et al., 2014). Torrefaction cause the biomass to lose its weight especially biomass with relatively high moisture content. 45% moisture content sample will reduce its weight three-fold compared to lower moisture content sample (Medic et al., 2012). This pre-treatment process is widely used in certain industrial process such as feedstock for boilers of biomass and coal cofiring, gasification fuel, and chemical industries' possible feedstock (Basu, 2018c). Torrefaction pre-treatment is highly beneficial for biomass such as EFB as it has high moisture content which will increase the calorific value and energy yield.

Moreover, addition of pelletization with torrefaction as pre-treatment of the biomass can further increase its mass energy density and volume energy density. This can be beneficial as it would decrease the transportation cost for the biomass. Pelletization works by densifying the biomass. Usually, the biomass will be pelletized after it has been torrefied, let cool, and grounded to specific size. Torrefaction increase the percentage of lignin content in the biomass due to major hemicellulose degradation. This provides extra lignin-active sites which influence better binding. Therefore, densification of torrefied biomass is less energy intensive compared to densification of untreated biomass (Basu, 2018c).

1.4 Characterisation of biomass

After the pre-treatment processes are done, the sample of each biomass is taken to several laboratory testing to measure the related characteristics of the respective biomass. For example, bomb calorimeter is used to measure the gross calorific value or the higher heating value (HHV) of the biomass. The apparatus is filled with high-pressure oxygen which is referred as the “bomb”. The sample is connected by fuse wire to the two electrodes inside the oxygen “bomb”. Surrounding the oxygen is deionized water as the heat medium to calculate the heat released. During the test, high voltage of electricity is flowed through the fuse wire by the electrodes thus, combustion of the sample occurs. The heat released is absorbed by surrounding deionized water until temperature of the water is stabilized. Accurate calculation of heat released by the combustion is then can be made. The value of heat released divided by the mass of the sample gives the HHV of the biomass sample (Basu, 2018a). Additionally, proximate analysis through thermogravimetric analyzer (TGA) need to be done to analyze the physicochemical properties of the torrefied biomass such as moisture content, fixed carbon, ash content, and volatile matter. Meanwhile CHNS analyzer is used to determine the carbon, hydrogen, and nitrogen contents (EFB). These analyses are useful for calculation of efficiency and total energy output during the combustion process.

1.5 Biomass boiler

Biomass is a cheap alternative for coal as boiler’s feed due to biomass is considered as waste material. By using biomass as the feed of a combustion process, it results in a carbon neutral process due to the gas emitted from the combustion process is theoretically equivalent to the amount that it has absorbed while growing. Thus, it is also called as carbon sink. Saidur et al. (2011) stated that substitution of diesel with biomass in the industrial boiler able to reduce the CO_2 emission greatly. This fact is demonstrated in the Figure 1.2 below. As much as 4,778 ton reduction in CO_2 emission is achieved by substituting 20% of diesel with biomass. Additionally, 11,946 of CO_2 emission is reduced by further substituting diesel by 50% with biomass. This shows great environmental impact to the usage of biomass boiler.

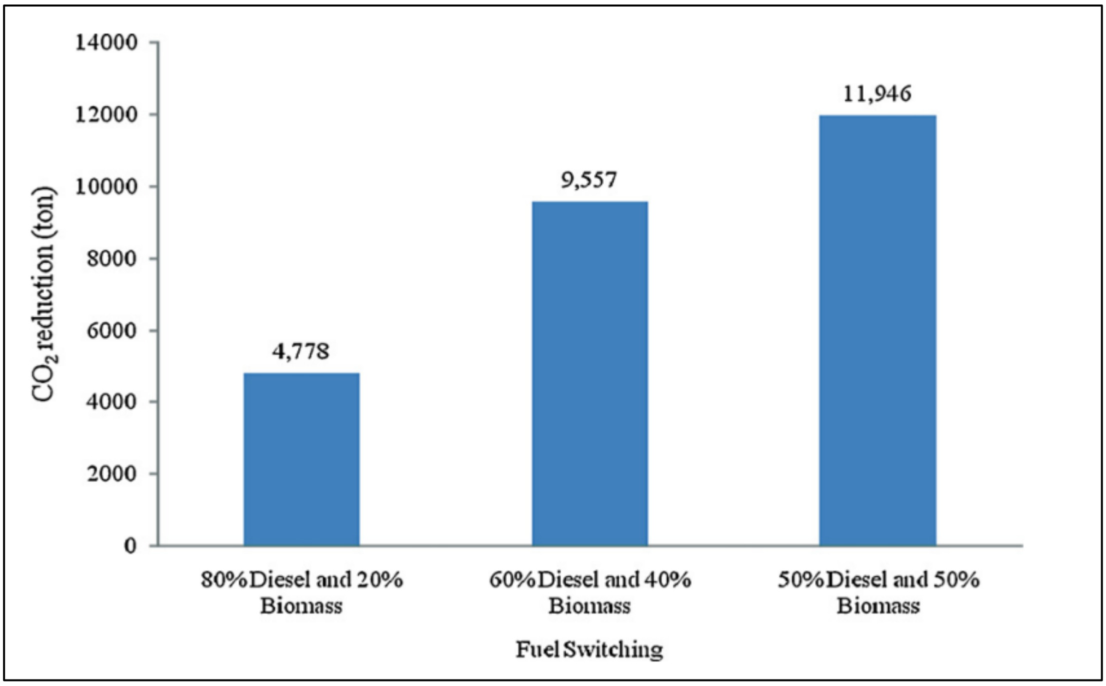

Figure 1.2 CO_2 reduction based on percentage of diesel switched with biomass. (Saidur et al., 2011)

Furthermore, the life cycle of biomass boiler is compared to natural gas boiler to identify its economic advantages. Wood-gasifying boiler would require a significantly high capital investment to run the system. However, in a run of 20-year life cycle, wood-gasifying boiler able to raise $19 million of revenue compared to natural gas boiler with no operating or energy saving.

1.6 Palm oil mill in Malaysia

Palm oil mill in Malaysia is producing at around 50% of the total global palm oil production with 11.5 million ton annually. The mill produced palm oil and kernel palm oil as the products of the main process. Meanwhile, some the major byproducts generated throughout the main process are mesocarp fibre (MF), palm kernel shell (PKS), empty fruit bunch (EFB), and palm oil mill effluent (POME). The biomass accounted to a large fraction of the dry matter mass thus the utilization of these biomass is important to minimize the process to handle the waste simultaneously using the waste effectively.

Combustion of the biomass to generates electricity is one of the ways of utilizing the biomass effectively. The biomass is used as a fuel to heat up high pressured steam in a boiler. The high pressure and temperature steam powered up the steam turbine which then generates electric power. The independent power generation system are also highly valuable as most of the palm oil mill located in Malaysia is in remote area where electricity grid connection points are more than 10 km from the palm oil mill location. On top of that, any amount of electricity surplus can also be supplied to the surrounding rural communities by decentralized power generation (Aghamohammadi et al., 2016).

1.7 Problem Statement

Abundance of biomass is produced by palm oil industry all around Malaysia. 103.94 million tons (Mt) of fresh fruit bunches (FFB) processed in 2017 in Malaysia, 22.87 Mt of EFBs, 14.03 Mt of MF, and 5.72 Mt of PKS were generated on wet basis (Sukiran et al., 2020). Biomass ratio in the normal boiler of a mill with 40 t/h FFB processing capacity, where 70% comes from MF and 30% from PKS. Whereas EFB is not utilized due to its high moisture content around 65-75 wt% which will affect the energy yield. High moisture content will use more energy as the moisture needs to be evaporated during the combustion. However, recent study shows that torrefied 67 wt% moisture content EFB exhibit higher energy potential with 48,453 MJ/h compared to PKS with only 29,706 MJ/h.

By torrefaction, the biomass able to increase the higher heating value (HHV), as well as its volumetric energy density. At 10 wt% moisture content of EFB, the biomass able to scale up the HHV from 16.47 MJ/kg to 19.29 MJ/kg. Not only that, but the energy yield also produced by the torrefied EFB able to reach up to 99.27%. To add, the operation of torrefaction occurs just under 300 °C thus torrefaction of EFBs is less energy-intensive and emits less gaseous product under mild reaction conditions compared with more severe thermal processes.

Plenty of the palm oil mill boiler only utilized PKS and MF as the feedstock. Thus, leaving the most abundant biomass from palm oil mill, EFB unused or used by other less efficient process. Torrefaction added combustion value to the EFB to be used in the boiler together with MF and PKS. In fact, EFB has potential to be the bigger fraction of the biomass fed to the biomass boiler once it is torrefied. The composition of EFB:MF:PKS can be optimized to match with the power requirement of palm oil mill. Apart from that, some operating conditions of the biomass boiler also have potential in optimizing the biomass boiler to generate more electricity.

Other than that, some palm oil mill is not independently generating power from biomass. Those mills used additional diesel as boiler fuel to compensate to the energy deficit due to insufficient power generated from biomass alone. Thus, several optimizations can be made such as optimization of biomass composition, boiler operating conditions, and increase in total feed mass flow rate to increase the power generation.

1.8 Objective

1. To study the effect of biomass torrefaction in optimizing power generation by steam boiler in palm oil mill.
2. To investigate the potential of power generation by addition of EFB as one of the boiler’s feeds in palm oil mill with varying biomass input ratio of EFB:MF:PKS.
3. To optimize the power generation in meeting the palm oil electricity demand by increasing the mass flow rate of the biomass input.

CHAPTER 2

LITERATURE REVIEW

2.1 Palm oil biomass

Malaysia has oil palm (Elaeis guineensis) with Tenera breed cross product which exhibit thick shell palm and shell-less palm (Asadullah et al., 2014). Oil palm fruit is mainly processed to produce crude palm oil and crude palm kernel oil which is the raw materials for oleochemical and biodiesel industry (Rupilius & Ahmad, 2007). Palm oil industry has been the major contributor of biomass production from the crude oil production (Abdulrazik et al., 2017). In a standard extraction rate of FFB, 22% of it is EFB, 5.5% is PKS, and 13.5% of it is MF that can be obtained from FFB based on wet basis. Most of the dry weight can be recovered as shown in Table 2.1(Loh, 2017).

Table 2.1 Oil palm biomass availability based on standard FFB extraction rate.

Type of oil palm biomass	Availability
MF	MF wet basis = 13.5% of FFB
	dry basis = 60% of MF wet basis
PKS	PKS wet basis = 5.5% of FFB
	dry basis = 85% of PKS wet basis
EFB	wet basis = 22% of FFB
	dry basis = 35% of EFB wet basis

2.2 Characterization of palm oil biomass feedstock

Calorific value (CV) or heating value is the heat energy content in biomass and released during combustion. It has two different but related value which are lower heating value (LHV) and higher heating value (HHV) (Mohd Idris & Hashim, 2021). These two values are connected by Equation 1.

Equation 1 Correlation of HHV and LHV.

$$LHV = HHV\left(1 - \frac{MC}{100}\right) - \frac{2.447MC}{100} \quad (1)$$

Where LHV is lower heating value of the fuel or biomass, HHV is higher heating value of the biomass, and MC is the moisture content of the biomass in percentage.

Equation 1 explained by HHV includes the latent heat of vaporization of the water inside the biomass into the calculation of the heating value. While LHV considered all the moisture has been converted into vapor phase (Madhu, 2020). Determination of HHV can be done by using bomb calorimeter. On the other hand, calculation by formula based on ultimate analysis is an alternative to approximate the HHV in case the laboratory analysis is unavailable to be done. Equation 2 is the relation of HHV to the constituent element of the biomass (Basu, 2018b).

Equation 2 Formula of HHV based on ultimate analysis.

$$HHV = 349.1C + 1178.3H + 103.4O - 15.1N - 21.1ASH\,\frac{kJ}{kg} \quad (2)$$

Table 2.2 shows the proximate analysis resulted from various study which includes heating value and Table 2.3 demonstrate the results ultimate analysis from several papers for untreated MF, PKS, and EFB biomass. Generally, all three biomasses have high carbon content that consists of carbon that can be used for combustion and the carbonate carbon content that cannot be combusted (Loh, 2017). However, high value of fixed carbon shows that these biomasses will produce high yield for thermochemical pre-treatment process such torrefaction (Sukiran et al., 2017).

The untreated oil palm biomass has high oxygen content which is around 50 wt% which will deteriorate the calorific value. Low calorific value also contributed by high moisture content like EFB. High moisture content will heavily affect the calorific value of a biomass by a fraction of heating energy consumed to vaporize the water inside the biomass. Apart from that, all three biomasses exhibit low Sulphur (S) and Nitrogen (N) content which translate to better combustion for environmental. This is due to S and N will cause undesired NOx and SOx gas to be released (Loh, 2017).

The calorific value collected shows that PKS has the highest value with 20.09 MJ/kg from with the highest carbon content 57.909 wt% (Loh, 2017). On the other hand, the lowest calorific value is 10.09 MJ/kg with the lowest carbon content 40.45% (Sukiran et al., 2020). This proves that high carbon content increases the calorific value or heating value of the biomass.

Table 2.2. Comparison of proximate analysis for untreated MF, PKS, and EFB.

	Gross calorific value (MJ/kg)	Moisture content (wt%)	Fixed carbon (wt%)	Ash content (wt%)	Reference
MF	17.15	10.1	9.4	5.6	(Mohd Faizal et al., 2018)
	19.06	37.09	–	6.1	(Loh, 2017)
	-	5.36	14.05	5.11	(Aziz et al., 2011)
PKS	19.45	4.9	13.7	2.2	(Mohd Faizal et al., 2018)
	20.09	12	–	3	(Loh, 2017)
	17.58	10	23	3	(Asadullah et al., 2014)
	-	8.72	15.31	2.16	(Aziz et al., 2011)
EFB	10.09	6.55	10.23	3.11	(Sukiran et al., 2020)
	18.88	67	_	4.6	(Loh, 2017)
	-	7.18	16.04	3.95	(Aziz et al., 2011)

Table 2.3. Comparison of ultimate analysis for untreated MF, PKS, and EFB.

	Carbon (wt%)	Hydrogen (wt%)	Nitrogen (wt%)	Oxygen (wt%)	Sulphur (wt%)	Reference
MF	43.17	6.09	0.9	–	0.9	(Mohd Faizal et al., 2018)
	46.396	9.283	0.391	50.212	ND	(Loh, 2017)
	47.62	5.26	0.57	45.63	0.44	(Aziz et al., 2011)
PKS	45.19	5.95	0.33	–	0.04	(Mohd Faizal et al., 2018)
	57.909	12.6	0.043	49.994	ND	(Loh, 2017)
	45.1	5.1	0.56	49.2	0.04	(Asadullah et al., 2014)
	50.18	5.54	0.49	43.35	0.42	(Aziz et al., 2011)
EFB	40.45	6.71	0.51	52.225	0.08	(Sukiran et al., 2020)
	48.715	7.858	0.249	48.179	ND	(Loh, 2017)
	45.81	5.74	0.43	47.54	0.48	(Aziz et al., 2011)

2.3 Pretreatment of biomass

Torrefaction treatment works by improving the chemical properties of the biomass which directly increase the combustion efficiency of industrial boiler (Mohd Faizal et al., 2018). Some of the benefit obtained by carrying out torrefaction pre-treatment of the biomass are (Panahi et al., 2018):

a. Increasing the calorific value or heating value

b. Better grindability

c. Lower moisture content

Besides, (Kaniapan et al., 2021) also agrees that torrefaction benefits the biomass by having better compressibility and enhanced material adhesiveness. In overall, the torrefied biomass has better thermal efficiency and higher overall calorific value which is highly valuable for combustion. Not only that, EFB also yield more lignin content and having better extractive concentration. Table 2.4 shows that averagely for MF, PKS, and EFB, the gross calorific value increased significantly after torrefaction of the biomass. The gross calorific value of high moisture content EFB after torrefaction almost double from the untreated EFB. This is due to moisture content decreased greatly after torrefaction process (Sukiran et al., 2020). Other than that, MF and PKS has increased gross calorific value to 23.38 MJ/kg and 24.5 MJ/kg, respectively. Figure 2.1 shows the mass yield is comparably lower than the volume yield. Mass loss is main resulted from moisture and oxygen content in the biomass. After the torrefaction, the biomass conserve energy content while losing mass thus, the energy is densified (Asadullah et al., 2014).

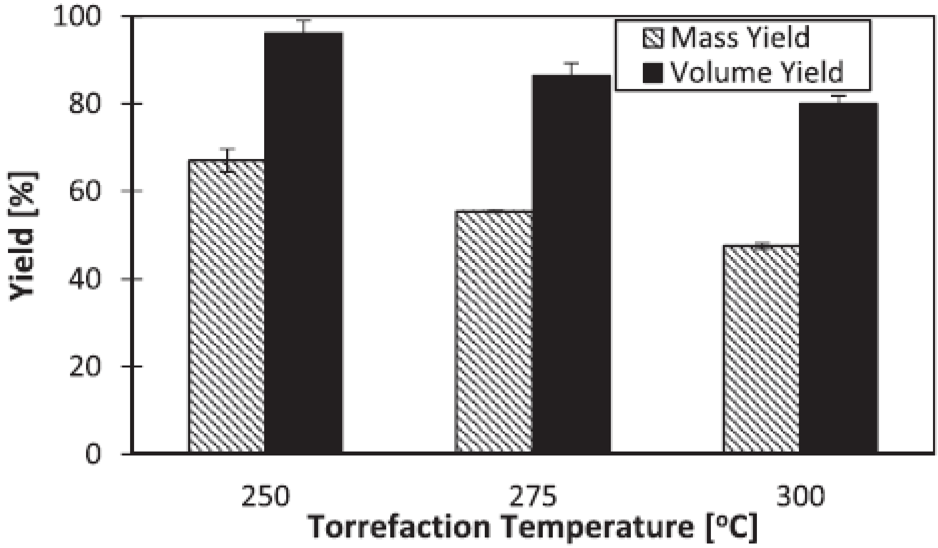

Figure 2.1 Mass and volume yield of torrefied (Mohd Faizal et al., 2018).

To bring into the energy generation context, the torrefied EFB energy properties is converted to energy potential and total potential electricity using Equation 3. From 40,000 FFB/h, 9200 kg EFB/h is generated. Using 9200 kg EFB/h as basis of the calculation, the biomass able to generate up to 41,782 kW for 10% moisture content with 7616.60 kg/h of torrefied yield (Sukiran et al., 2020).

Equation 3 Formula of energy potential of the torrefied EFB.

$$Energy\ potential = Torrefied\ EFB\ yield, \% \times HHV_{torrefied\ EFB} \quad (2)$$

$$1 \frac{MJ}{h} = 0.27778\ kW$$

These values are important as a component to calculate the efficiency and total energy output from the combustor. In palm oil mill, boiler is the equipment to cogenerate power and heat which will be supplied back to power up the palm oil mill.

Table 2.4. Comparison of gross calorific value of torrefied MF, PKS, and EFB.

	Gross calorific value (MJ/kg)	Energy yield (%)	Biomass temperature (°C)	Residence time (min)	Reference
MF	23.38	–	300	40	(Mohd Faizal et al., 2018)
PKS	24.5	94.7	300	15	(Asadullah et al., 2014)
EFB	19.2	97.67	270	60	(Sukiran et al., 2020)

2.4 Industrial boiler in palm oil mill

Besides, Talib & Abd Majid (2016) studied the boiler in Sei-Manggaris Palm Oil Mill cogeneration plant. The cogeneration system used 35 ton/h boiler paired with 1400 kW design capacity steam turbine operating at 21 barg dry saturated steam. The exhaust steam from the turbine is released at 3.1 barg pressure. The study used the biomass feed with calorific value of 14,250 kJ/kg basis for the calculation of the boiler. Following that, the boiler operates with 5,820 kg/h of feed in a 45 ton FFB/h processing capacity while 7020 kg/h of feed in a 60 ton/h mill processing capacity. Additionally, other boiler specification is as listed in the Table 2.5 below. Based on the boiler configurations, it able to generate 18 kW/ ton of FFB processed. Based on the analysis, the power generated is insufficient to meet the palm oil mill electricity demand which is 22 kW/ton of FFB processed. Therefore, 0.8 L/ton FFB is consumed to generate the remaining power demand. The consumption is cited to be higher than the industrial standard which is 0.56 L/ton FFB.

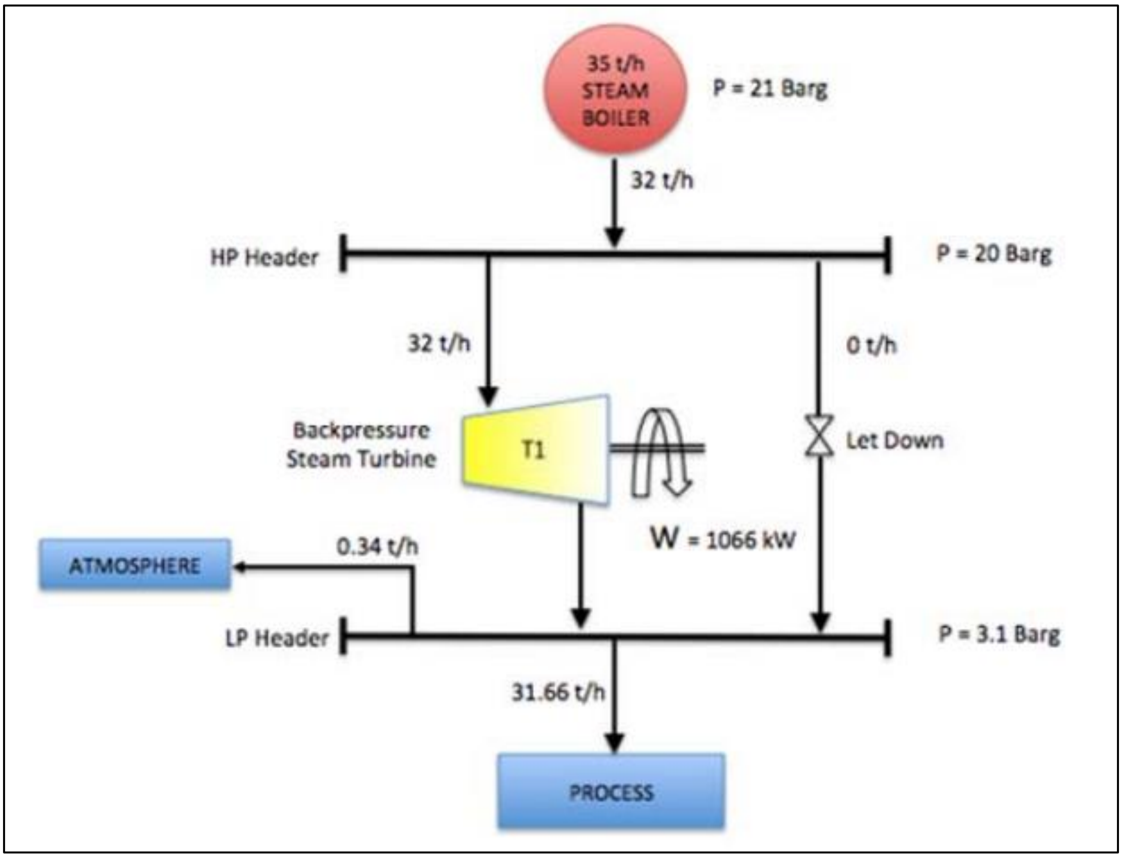

Figure 2.2 Sei-Manggaris palm oil mill cogeneration plant.

Table 2.5 Cogeneration system specification.

Parameter	Unit	Value
Thermal efficiency	%	57.50
Electrical efficiency	%	3.60
Cogeneration efficiency	%	61.10
Specific steam used	kg/ton FFB	527.78
Maximum power generation	kW	1,066.67
Specific power generation	kW/ton FFB	18.00
Boiler fuel rate	kg/h	5,820.00
Boiler efficiency	%	80.60

Abdul Razak & Abdulrazik (2019) stated that its study targeted to generate 1.3 MW of power generated by its biomass boiler by using torrefied EFB pellet in the biomass-based cogeneration plant. The study used ASPEN Plus software to model and simulate the overall plant as shown in Figure 2.3. Other than that, General Algebraic Modeling System (GAMS) is the optimization tool that involve integer problem. This two software is synergized to model and improve the cogeneration plant.

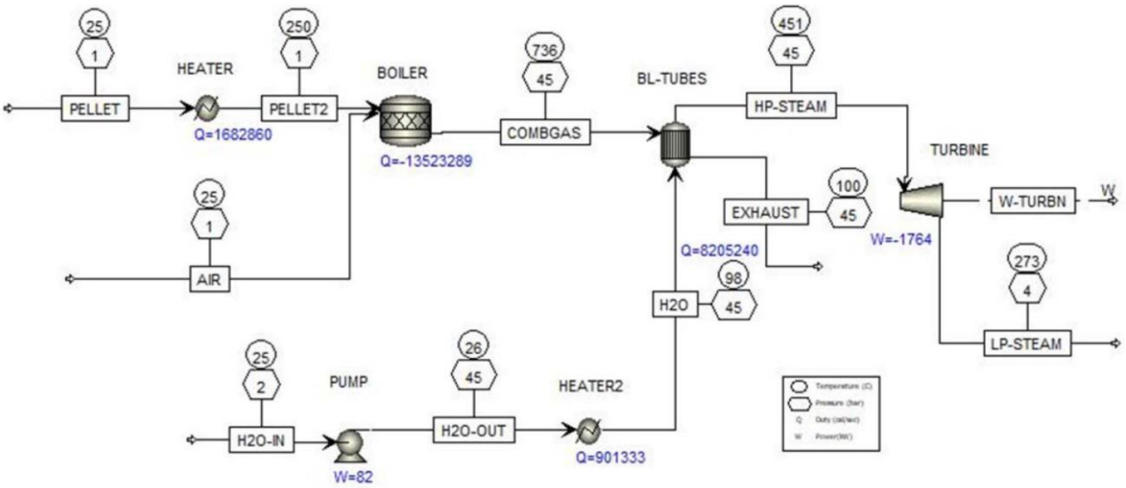

Figure 2.3. Flowsheet of biomass-based cogeneration plant in ASPEN Plus Abdul Razak & Abdulrazik (2019)

2.5 Palm oil mill capacity and electricity

Palm oil mills are varied based on its fresh fruit bunch (FFB) processing capacity. A study by (Nasution et al., 2014) demonstrate a set of data for palm oil mills located in North Sumatera, Indonesia. Based on that study, it is known that 40% of the palm oil mills has around 30 tons FFB/h of capacity. Meanwhile, 14% of the palm oil mill process below 30 tons FFB/h and similarly, palm oil mill with capacity 45, 50, 60 tons FFB/h takes up 14% of the palm oil mill in North Sumatera, respectively. Following that, most of the mill produced 20% of EFB, 7% of PKS, and 13% of MF biomass from palm oil processing (Nasution et al., 2014).

Utilization of EFB as one of boiler's feed is justified by the high amount compared to MF and PKS to increase the power generation and reduce the waste to be handled.

Consequently, the power generated from each category of the mill is also discussed. It was cited that 30 tons of FFB/h processing capacity capable to generate up to 12 MW. As the processing capacity is doubled to 60 tons of FFB/h, the cogeneration system able to almost double the power generated with range of 17 MW to 20 MW. The power generated is said to be excess as much as 9.7kW/ton FFB which have the potential to distribute to the nearby local communities (Nasution et al., 2014).

Based on Warman, Iqbal, & Fahmi (2019), biomass from 45-ton capacity of palm oil mill PT. Djaja Putra Indonesia utilize 502.4 kW of electricity for overall mill to plant. Table 2.6 shows the breakdown of electricity used in each station. To design a biomass boiler, the energy output must be able to cater the energy requirement according to its palm oil mill capacity.

Table 2.6. Electricity requirement in palm oil mill (Warman et al., 2019).

Processing station	Electricity energy requirement (kW)
Sterilizer	31.6
Thresher	40.8
Pressing	70.4
Clarification	76.4
Seeds and pulp	187.3
Boiler	96
TOTAL	502.4

On the other hand, higher processing capacity will result in higher power consumptions and higher rate of biomass production. Table 2.7 compared the biomass utilized based on the processing capacity of different palm oil mills. Mill B shows a considerably high fuel rate for boiler even at processing capacity of 30 FFB/ton. The increment of fuel rate for the boiler is due to the addition of EFB as one of the boiler's feeds. Subsequently, Table 2.8 demonstrate the power demand and the potential power generated from the boiler for each palm oil mill.

The specific energy to operate the mill for every tonne FFB processed is reduced as the processing capacity increased. However, the power demand is still increasing due to operating extra operational unit such as bigger EFB treatment plant. However, higher the electricity surplus from larger mill able to generate more profit as the processing capacity increases by utilizing the available biomass in the mill (Nasrin et al., 2011).

Table 2.7 Palm oil mill processing capacity and boiler fuel rate for palm oil mill. (Nasrin et al., 2011)

Mill	Processing capacity (ton FFB/h)	Biomass utilization (ton/h)				Ratio	Calorific value (kJ/kg)
		MF	PKS	EFB	Total		
A	20	2.34	0.96	-	3.30	71:29:0	13535.00
B	30	3.12	0.18	3.04	6.34	49:3:48	10882.00
C	40	3.90	1.68	-	5.58	70:30:0	13594.00
D	40	3.77	1.62	-	5.39	70:30:0	13594.00
E	50	5.25	2.10	-	7.35	71:29:0	13535.00
F	54	5.62	2.27	-	7.89	71:29:0	13535.00

Table 2.8 Palm oil mill power demand and profit from power surplus. (Nasrin et al., 2011)

Mill	Total electricity potential (kW)	Mill electricity demand (kW)	Parasite and EFB treatment plant (kW)	Total electricity surplus (kW)	Profit (RM/year)
A	863.795	400	350	113.795	114,705.00
B	1295.692	600	350	345.692	348,457.50
C	1727.589	800	350	577.589	582,210.10
D	1727.589	800	350	577.589	582,210.10
E	2159.487	1000	350	809.487	815,962.60
F	2332.246	1080	350	902.246	909,463.60

2.6 Parametric optimization of the industrial boiler

Based on Nasution et al. (2014), it is stated that palm oil mill operating with 30 tons FFB/h processing speed would only require 75 MJ of electricity and 1790 MJ of steam to run. Analyzing the energy generated from the palm oil mill biomass, Figure 2.4 shows the generation of energy with 1 ton of FFB and 30 tons FFB/h as the basis. Note that, this calculation is excluding EFB as the feedstock of the boiler. The biomass able to be converted to total of 1900 MJ for both steam and electricity and produce about 9.7 kW of electricity after usage of milling process.

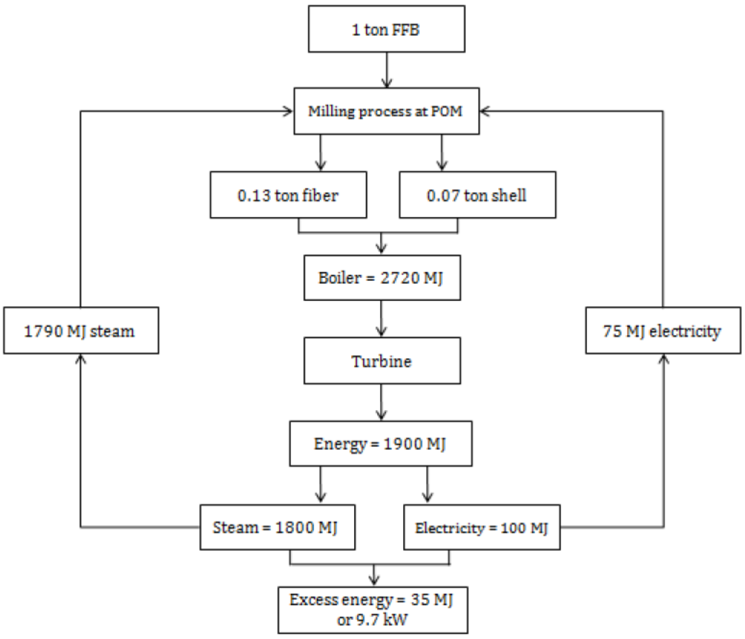

Figure 2.4. Energy flow diagram from boiler with MF and PKS as feedstock (Nasution et al., 2014)

Figure 2.5 shows the calculated energy production by addition of EFB as the boiler feedstock. The total amount of energy generated from the turbine almost reaching double of the boiler without EFB as feedstock, 3750 MJ. This shows promising potential of energy output by combining EFB with PKS and MF as the feedstock of the boiler with appropriate ratio (Nasution et al., 2014). Not only that, the overall power potential based on the palm oil mill capacity also surged to over double the value power generated compared to utilization of MF and PKS only. Figure 2.6 demonstrate the value for power potential from biomass boiler based on mill processing capacity.

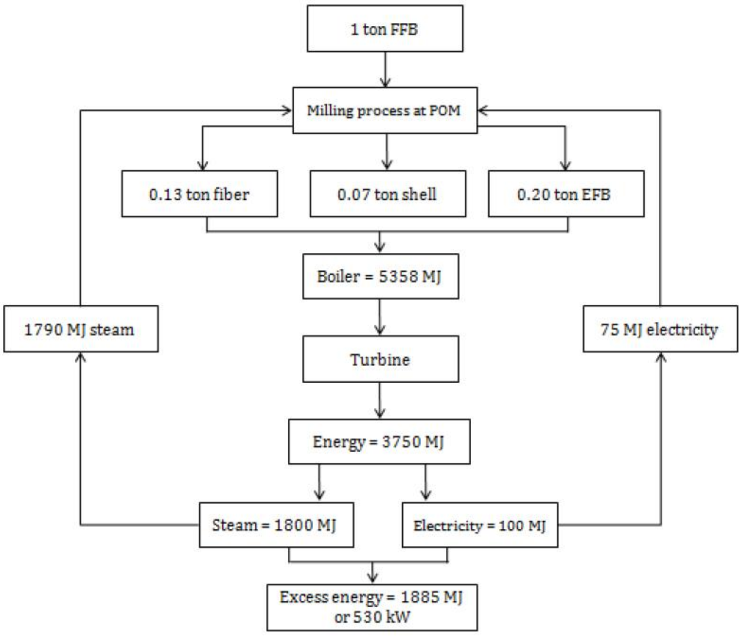

Figure 2.5. Energy flow diagram from boiler with MF, PKS, and EFB as feedstock. (Nasution et al., 2014)

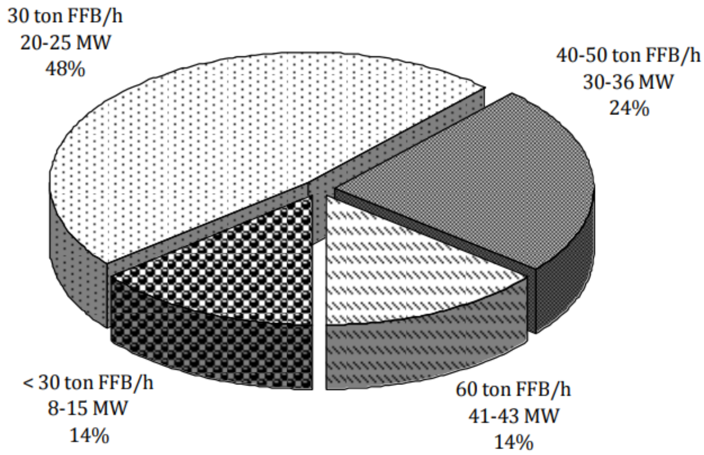

Figure 2.6 Power potential based on palm oil mill processing capacity. (Nasution et al., 2014)

Table 2.9. The value of power generated at different pellet flow rate

Pellet Flow Rate (kg/s)	2	3	4	5
Power Generated (MW)	1.347	1.458	1.599	1.764

Table 2.10. The value of power generated at different water flow rate

Water Flow Rate (kg/s)	11.5	12.0	12.5	13.0	13.5
Power Generated (MW)	1.764	4.689	1.631	1.591	1.569

Table 2.11. The value of power generated at different air flow rate

Air Flow Rate (kg/s)	34.5	35.5	36.5	37.5	38.5	39.5
Power Generated (MW)	1.558	1.622	1.691	1.764	1.841	1.920

Table 2.12. The value of power generated at different boiler temperature.

Temperature (°C)	660	680	700	720	740	760	780	800	820
Power Generated (MW)	1.387	1.469	1.564	1.671	1.789	1.916	2.043	2.170	2.296

Table 2.13. The value of power generated at different boiler temperature (Continued).

Temperature (°C)	840	860	880	900	920	940	960	980
Power Generated (MW)	2.421	2.545	2.668	2.790	2.912	3.033	3.152	3.271

Table 2.9 to Table 2.13 are the data obtained from their ASPEN Plus simulation with various manipulated variables. The simulation resulted in the maximum power generated is at water flow rate 11.5 kg/s and pellet flow rate at 11.5 kg/s. Besides, the power generated increase as the air flow rate increases up to 39.5 kg/s producing 1.920 MW. Similarly, increase in boiler temperature directly increase the power generated. Mainly, the research study is motivated by

Abdul Razak & Abdulrazik (2019) along with other studies such as Nasution et al. (2014) and Talib & Abd Majid (2016).

Based on the reviewed literatures, there is no study includes all three EFB, MF, PKS as the torrefied biomass feed for the boiler. Additionally, the literatures reviewed did not utilize the torrefaction to increase the power generation potential from the biomass. Thus, optimization of the palm oil mill biomass boiler is important to realize the potential of power generation from biomass produced in the palm oil mill. Not only that, Talib & Abd Majid (2016) also stated that biomass boiler needed diesel as an additional fuel to meet the power requirement to run the palm oil mill. Thus, optimization of biomass boiler in this research may contribute to meet the electricity demand of the palm oil mill and may also contribute to the surrounding rural communities.