

## Production Cost Assessment of Palm Empty Fruit Bunch Conversion to Bio-Oil via Fast Pyrolysis

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**Abstract**— Production cost assessment was based on palm oil mill of 30 metrics tons FFB/h capacity that produced EFB residue at app. 20 % wt of the initial FFB fed to the plant. The bio-oil plant will be located in the palm oil mill complex to eliminate the transportation cost of the EFB feedstock. The process included in this calculation is chopping, drying, grinding, pyrolysis, solid removal, bio oil recovery, and storage. The production cost is influenced by the amount of bio-oil production, material cost, operational cost including labor and utility cost. The sensitivity analysis shows that feedstock price drives the production cost. The result concludes that for the current condition, the bio-oil production cost from palm empty fruit bunch seems promising to be implemented in Indonesia. The best option is to have the bio-oil plant integrated with the palm oil mill, where in this case the EFB can be kept at no cost, off the market influence.

**Keywords**— Fast Pyrolysis, Bio-oil, Palm Empty Fruit Bunch, Production Cost.

### I. INTRODUCTION

Energy is one of the important factors for the life of human kind; it is a driving force for the development. The quality of life of people is even often regarded as how much energy consumed for living. The growth of the world energy consumption in the last two decades has been amazing as can be seen in Fig. 1. However, as shown in Fig.2, the source of energy to fulfil such consumption mainly relies on non-renewable fossil fuels with world reserve capacities decreasing continuously. The reliance on fossil fuel without any effort of conservation will eventually lead to the energy crisis within not in a distant future. Thus, it is required to re-orient the attention to other source of energy in order to ensure energy security for current usage and for the future generations to come.

Efforts have been made to conserve the fossil fuel by looking for renewable natural resources, e.g. wind, solar, tidal wave, biomass, etc. However, these types of sources are heavily site-dependent and sometimes require collecting activity in case of biomass. As has been already known, the usage of fossil fuels are for electricity generation, and in the form of oil/gas, used as fuel for vehicles and energy source for daily life activity in the households.

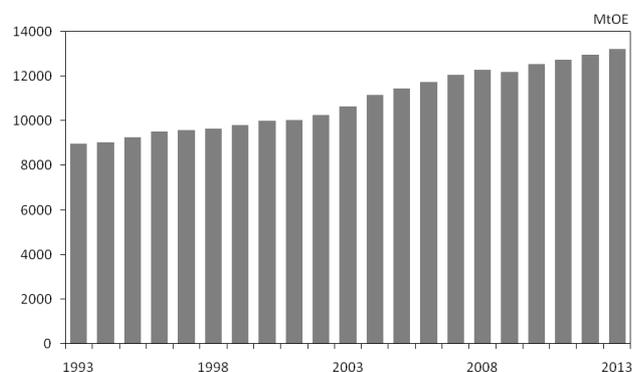


Fig. 1 World Energy Consumption [1]

Either as electricity or liquid/gas, the fossil fuel is easy to be transported. In contrast to fossil fuel, the wind, solar and tidal wave as energy sources cannot be transported to other places in its original form. It can only be transferred when these are converted to electricity and connected to the grid for transmission. Biomass in its original form can be transported to other places; however its bulky mass creates difficulties and induces cost on transportation due to its low energy content. From the view point of transportation and ease of use, the liquid type fuel is convenient; it is relatively easy to handle and can also be used to fuel the engine. Therefore the liquefaction of the biomass will lessen, if not

eliminate, the burden of transporting the fuel in its original form.

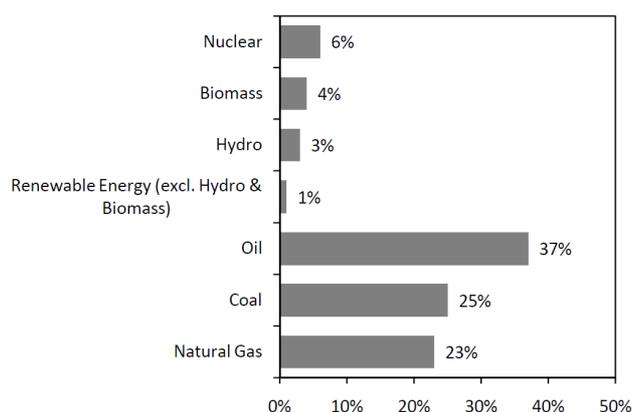


Fig. 2 World Energy Consumption by Resources, 2009 [2]

There are many sources of biomass, from plantation residue to the organic waste from daily life activities. For most of the cases, these biomass sources need collection and separation to get enough amounts for conversion and to make it feasible economically. For the case of Indonesia, the available and already collected biomass is palm empty fruit bunch. The empty fruit bunches are readily collected at the palm oil mill, thus it eliminates one of the problem commonly arise from biomass waste biomass utilization, i.e. collection.

Table 1 shows the biomass source potential from palm oil mills in Indonesia in 2010 as reported in [3]. It is clear from the figure that empty fruit bunch readily collected in the palm oil mills is the most abundant among others. Palm shell and fiber are commonly used as fuel to generate heat in palm oil mills whilst palm condensate has its amount reduce by year due to the increasing palm oil mill efficiency. Thus, it left only empty fruit bunch from the palm oil mill that has not been really utilized except as soil fertilizer for the palm trees.

TABLE I  
BIOMASS SOURCE POTENTIAL FROM PALM OIL MILL IN INDONESIA, 2010

Description	Quantity	Percentage
CPO Production, tons (assumed 24 % yield)	20,000,000	24.00 %
Fresh Fruit Bunch (FFB), tons	83,000,000	100.00 %
Palm shell, tons	5,312,000	6.40 %
Palm Fibers, tons	11,952,000	14.40 %
Empty Fruit Bunch (EFB), tons	17,430,000	21.00 %
Palm Condensates, tons	11,205,000	13.50 %
Palm Fatty Acid Distillate	813,400	0.98 %

Therefore, the current work will be focused on the techno-economic analysis of the fuel oil production from palm empty fruit bunch through fast pyrolysis process.

## II. FAST PYROLYSIS

Pyrolysis is a process of heating a substance in an oxygen-free environment. This process may result three types of product, i.e. liquid, gas and solid. The amount of

each product type can be adjusted by adjusting the temperature and residence time of the process. Table 2 resumes the pyrolysis process aiming to produce liquid, solid and gas products.

It is shown in Table 2 that fast pyrolysis process can give much liquid from the pyrolysis processes of the biomass feedstock [4]. In principles, the biomass undergo fast pyrolysis will decompose very rapidly to generate mostly vapors and aerosols and some charcoal and gas. After cooling and condensation, a dark brown homogenous liquid is formed which has a heating value approximately half of that petroleum fuel.

TABLE II  
TYPICAL PRODUCT WEIGHT YIELDS (DRY BASIS) OBTAINED BY DIFFERENT OF WOOD PYROLYSIS

Mode	Condition	Liquid	Solid	Gas
Torrefaction (slow)	290 °C, solid residence time 10 – 60 min	0% (if condensed, up to 50%)	80%	20%
Gasification	750 – 900 °C	5 %	10% char	85%
Carbonisation (slow)	400 °C, long vapour residence time hours → days	30%	35 % char	35%
Intermediate	500 °C, hot vapour residence time 10 – 30s	50% in 2 phase	25% char	25%
Fast	500 °C, short hot vapour residence time 1s	75%	12% char	13%

A high yield of liquid is obtained from biomass with low ash content. Another important requirement in fast pyrolysis, due to a very short vapor residence time, is bringing the reacting biomass particles to the optimum process temperature in an instance. This objective can be achieved by using small particles in the fluidized bed so the heat can be transferred very fast. In addition to that, it is required that the exposure of biomass particle to lower temperature be minimized to avoid the formation of charcoal.

The current common bio oil yield is up to 75 wt% on a dry-feed basis as shown on Table 2 with the remaining product of char and gas can be used to generate heat required for the process. To minimize the water content of the product oil, the feed stock's moisture content of less than 10% is preferable.

In general, there are three stages to get the more useful product oil from biomass, i.e.:

- Feed preparation and treatment including storage and handling
- The fast pyrolysis process conversion including fast quenching and oil collection
- Refining and/or conversion the bio oil product to a marketable end-product

### III. REVIEW OF THE PREVIOUS WORKS ON TECHNO-ECONOMIC ANALYSIS

Wright et al. [5] has developed the techno-economic models for assessment of corn stover to liquid conversion via fast pyrolysis followed by subsequent product upgrading by hydrotreating and hydrocracking in 2010. There were two scenarios in their model. First scenario deals with the hydrogen (required for hydroprocessing) production on site by reforming bio oil whilst in the second scenario the required hydrogen is purchased from outside source. The study shows that the production cost is US\$ 0.21/liter for the plant capacity of 2,000 metric tons per day of corn stover feedstock can be achieved.

Techno-economic assessment of a fast pyrolysis plant producing 16 tons/day of bio-oil was conducted by Ringer et al. [6] in 2006. Their study includes feed handling and drying, pyrolysis, char combustion, product recovery and steam generation. Based on a 550 tons/day wood chips (50% moisture content) feedstock, the cost of bio-oil for fully equity plant and 10% internal rate of return is US\$ 7.62/GJ on a lower heating value (LHV) basis.

A computer program was developed by Cottam and Bridgwater [7] in 1994 to assess and compares the economic and technical aspects on biomass flash pyrolysis followed by subsequent upgrading and refining to produce higher value and more marketable liquid fuel products. The result shows that an energy self-sufficient system is feasible utilizing the by-product char and off-gas as fuel for combustion to generate required heat of pyrolysis process temperature below 540 °C.

A model of biomass-derived oil production system was developed by Gregoire et al. [8] in 1994. The system consists of silo dryer, pyrolysis reactor, furnace, steam turbine and bio oil recovery section. It was found that method of financing (equity or debt), feedstock cost, plant availability, plant size and depreciation schedule are the parameters that significantly affect the profitability of the plant.

Rice husk conversion to liquid fuel via fast pyrolysis with catalytic treatment was studied in 2000 by Islam and Ani [9]. The processes being considered were Fluidized Bed Fast Pyrolysis (FBFP) and Fluidized Bed Fast Pyrolysis with Catalytic Treatment (FBFPCT) for three different scale plants of 0.3, 100 and 1000 kg/h of feedstock. FBFP was found to be economically better than FBFPCT. The plant capacity of 1000 kg/h appeared to be economically feasible.

Hsu [10] performed a life cycle analysis of the production of gasoline and diesel fuel from forest residues via fast pyrolysis and hydroprocessing. The works includes forest residue production and harvesting, preprocessing, feedstock transportation, fuel distribution and vehicle operation. It was assumed that the electricity and supplemental natural gas for the hydrogen plant are supplied from outside. The study concluded that the pyrolysis-derived gasoline and diesel fuel have lower Green House Gases emission and higher Net Energy Value in comparison with conventional petroleum fuel.

The transport cost for energy crops to be used in biomass pyrolysis plant networks was analyzed by Rogers and Brammer [11] in 2009. It was found that the key parameter

was the number of round trip a day a truck could make rather than the distance covered. It was also found that producing bio-oil near to the field stores and transporting the bio-oil to a central plant would only be cost-effective for large generation plants.

Milling and pelletizing are found to be energy intensive processes based on the biomass feedstock preparation study by Casado and Pascual [12]. Rape straw and poplar wood were chosen as samples for the analysis. Comminution methods used for size reduction involved three steps, i.e. chopping or shredding, cutting and milling. However, this study was based on the feedstock for gasification process where the final feedstock size is 10 mm particles.

### IV. MODEL OF BIO OIL PRODUCTION VIA FAST PYROLYSIS

#### A. The basis of the model

There are numerous palm oil mills with different capacity scattered in Sumatera and Kalimantan islands of Indonesia. Table 3 shows the example of palm oil mills in Riau Province.

TABLE III  
PALM OIL MILLS IN RIAU PROVINCE

No	Plant	Location	FFB Capacity (metric ton/hour)
1	Sungai Tapung	Kampar	60
2	Kebun Tandun	Kampar	40
3	Trantam	Kampar	60
4	Sungai Garo	Rokan Hulu	30
5	Sungai Rokan	Rokan Hulu	60
Total			250

The plant capacity of 30 metric tons/h of FFB feeding can be deemed as the minimum economical size of the palm oil mill plant. Thus, for the current techno-economic analysis of bio-oil plant, the EFB residue from the palm oil mill of 30 metric tons FFB/h will be considered. As shown in Table 1, the EFB residue is approximately 20 wt.% of the initial FFB fed to the plant. For palm oil mill, the 30 tons FFB/h capacity correlates to the EFB production of 6 metric tons/h. This number of 6 metric tons/h of EFB will be used to feed the bio-oil plant.

The bio-oil plant will be located in the palm oil mill complex to eliminate the transportation cost of the EFB feedstock.

Table 4 shows the key assumptions for the current analysis as derived from Wright report [5]. Some of the assumptions were taken from other sources related to EFB pyrolysis.

TABLE IV  
KEY ASSUMPTION OF THE PROCESS

Sub-system	Description	Assumption
Chopping	Particle size reduction to 5 cm long of EFB fiber	Incoming EFB is in the form of bunch weighted 6 kg
Drying	EFB drying to 7 % moisture	Drying at 100 °C at atmospheric pressure
Grinding	Particle size reduction to 0.5 mm	Incoming EFB average size is as describe in Chopping Description

Pyrolysis	EFB conversion to bio oil, char and gas	500 °C and 1 atm 2.75 weight ratio of fluidize gas to EFB. Heat provided by char combustion.
Solid removal	Removal of entrained solid particles from vapour stream	Removal efficiency of 90% by using cyclone
Bio-Oil recovery	Collection of condensing vapors	Rapid condensation to about 50°C 100% collection of aerosol
Storage	Storage of bio-oil and char	4 weeks storage capacity

### B. General Process Flow Diagram

For the purpose of the techno-economic analysis, the Fig.3 general process flow diagram as adapted from Wright [5] will be used. However, the upgrading sub-system will not be covered in the current work.

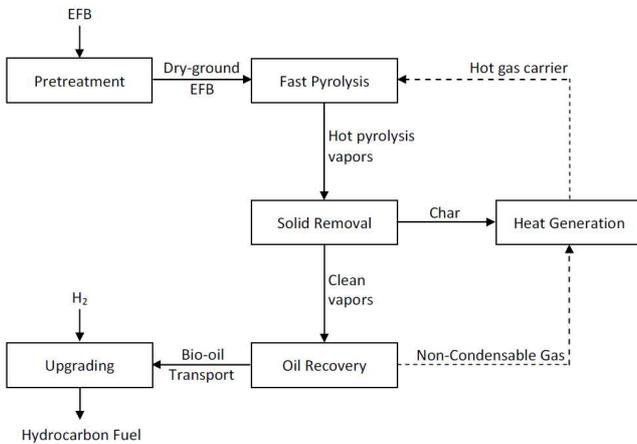


Fig. 3 General biomass to liquid fuel conversion process flow diagram

### C. Palm EFB Preparation

Pretreatment of the EFB consist of chopping, grinding and drying. The EFB with 50% moisture content from the palm oil mill is fed to the crusher and grinder. The incoming EFB in the form of bunch with average diameter approximately 30 cm is chopped to the average size of 1-5 cm particle and then ground to the maximum particle size of 500  $\mu\text{m}$ . This fine particle then moves to the dryer to reduce its moisture content down to 7%.

The energy required for chopping and grinding of a material is determined by the hardness of the material. There is no report available regarding the grindability of EFB. However it is approximated that EFB has the Hardgrove Grindability Index (HGI) value of 20-30 that modified from [13], whilst low rank coal has the value of approximately 50.

### D. The Pyrolysis

Prior to the admission to the pyrolyzer, dried-fine EFB particles undergo preheating altogether with the carrier gas which is introduce at this stage. At the pyrolyzer, the feedstock is heated at the temperature of 500°C and atmospheric pressure. To aid rapid heating of the feedstock

at the order of less than 1 second vapors residence time, a weight ratio of carrier gas to biomass of 2.75 is chosen base on the Wright [5] research.

Various yield of bio-oil from fast pyrolysis of biomass has been reported by many researchers with the current maximum yield as exemplified at Table 2. However, researches by Sulaiman [14] and Abdullah [15], conducted specifically for EFB shows the bio-oil yield of approximately 55% and 61% respectively were achieved. Thus, the current work take the more conservative approach by choosing approximately 60% bio oil yield with the remaining char and gas product share almost the same yield.

There are various types of pyrolyzer considered by many researchers. However bubbling-bed type was chosen due to the availability of information, technological development and economical advantages in comparison with circulating bed, ablative process, auger type, etc.

### E. Char and particulate separation

The cyclone was used for solid removal entrained in the liquid vapors and aerosol coming out from the pyrolyzer. It is assume that a series of cyclones is able to remove 90% of the particles entrained in the stream. In addition, a series of filter can also be applied for solid removal as a secondary unit to improve solid removal efficiency; however this is not the case of the current work.

The collected char is send to the combustor to provide heat required for pyrolysis process and preheating of the feedstock. The proximate and ultimate analyses followed by bomb calorimeter analysis are required to determine the energy content of char. However, for the current work the Higher Heating Value of char EFB is approximated to be 24.1 MJ/kg as adapted from Raveendran [16].

### F. Bio oil Collection

The bio-oil collection employs indirect contact heat exchanger to transfer heat from the vapors to water. After most of the vapors are condensed to oil, the remaining droplet of aerosol is transfer to an Electro-Static Precipitator (ESP) to collect all the remaining char and ash entrained in the vapors.

The gas leaving the ESP is passed through a combustor, heated up, and then reused as carrier gas to the pyrolyzer. Meanwhile, the liquid streams coming out from the condenser and ESP is then collected as bio-oil.

## V. PRODUCTION COST ANALYSIS

The current economic study assesses the production cost of the bio-oil. To achieve this goal, it requires the knowledge mostly on material balance, energy requirement and operational cost. In an aid of determining such requirement, a more detailed process flow diagram of the process is shown in Fig. 4 which is the elaboration of the previous Fig. 3 with the elimination of upgrading pathway.

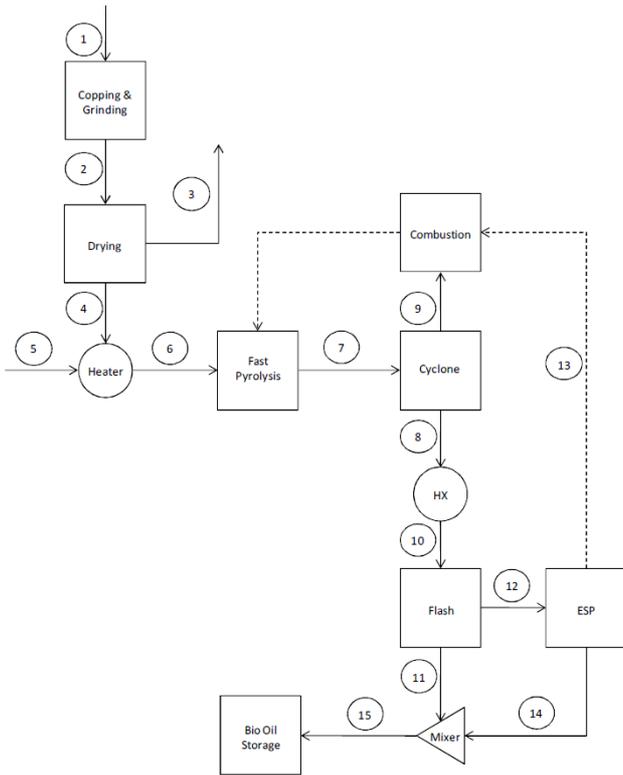


Fig. 4 Process flow diagram of EFB conversion to bio-oil

#### A. Mass Balance and Energy Requirement

Based on the developed model, constraint and assumption made in Section 4 and referring to the process flow diagram in Fig. 4, the following material balance of the process was simulated as exemplified in Table 5.

TABLE V  
MATERIAL BALANCE OF EFB CONVERSION TO BIO-OIL

Stream No	Stream			Material Flow (kg/h)					
	T (C)	P (bar)	EFB	H <sub>2</sub> O	Gas	Bio-Oil	Char	Ash	Total
1	25	1.013	3000	3000	-	-	-	-	6000
2	25	1.013	3000	3000	-	-	-	-	6000
3	100	1.013	-	2774	-	-	-	-	2774
4	100	1.013	3000	226	-	-	-	-	3226
5	100	1.013	-	-	8871	-	-	-	8871
6	250	1.013	3000	226	8871	-	-	-	12097
7	500	1.013	-	339	9448	1774	534	1.98	12097
8	500	0.997	-	339	9448	1774	53	0.20	11614
9	500	0.997	-	-	-	-	481	1.78	482
10	150	0.997	-	339	9448	1774	53	0.20	11614
11	50	1.013	-	215	3	1476	43	0.15	1737
12	50	1.013	-	124	9445	298	11	0.05	9878
13	50	1.013	-	-	9445	-	-	-	9445
14	50	1.013	-	124	-	298	11	0.15	433
15	50	1.013	-	339	3	1774	53	0.20	2169

#### a. Chopping and grinding power requirement

Energy required for chopping and grinding of 6,000 kg/h of wet EFB is estimated to be 60 kW that estimated from [17] for cage mill grinder which correlates to 10 kWh/ton by using cage mill type grinder.

#### b. EFB Drying energy requirement

The required energy for 6,000 kg/h EFB with moisture content of 50% can be approximated by bringing the temperature of H<sub>2</sub>O part of the EFB from 25°C to 100°C at atmospheric pressure. 50% of moisture content implicates the amount of water need to be removed from the EFB is approximately 2,774 kg/h in order to get the moisture content of the EFB down to 7%. However, the amount of H<sub>2</sub>O need to be heated up is actually 3,000 kg/h since the moisture content of the EFB is uniform throughout the EFB, thus cannot be heated up partially. The required energy can then be estimated using mass and enthalpy of H<sub>2</sub>O at 25 and 100°C which are 104.92 and 2675.59 kJ/kg respectively at atmospheric pressure.

$$P = 3,000 \frac{\text{kg}}{\text{h}} \times (2,675.59 - 104.92) \frac{\text{kJ}}{\text{kg}}$$

$$= 7,712,010 \text{ kJ/h}$$

Actual drying will require heating up of the whole bunch or shredded/ground EFB in order to remove the trapped moisture. However, the above simplicity method is sufficient since the actual temperature of the EFB comes from the mills is more than 50°C. Thus considering only H<sub>2</sub>O heating can be deemed sufficient for the current stage of study.

#### c. Energy requirement for feedstock preheating and pyrolysis process

Energy required for feedstock preheating and pyrolysis process is estimated using the data from Table 5 Material balance. This energy is approximated by energy requirement to heat up the 8,871 kg/h carrier gas at Stream 5 from 100°C to 500°C at atmospheric pressure. This carrier gas at Stream 5 entering the Heater has the initial temperature of 100°C since it has pass through the combustor. For simplicity, the carrier gas is assumed to be nitrogen gas which has a specific heat at constant pressure (cp) of 1.04 kJ/kg-K [18] at atmospheric pressure. Thus, the required energy for the preheating and pyrolysis process is as follow:

$$Q = 8,871 \frac{\text{kg}}{\text{h}} \times 1.04 \times \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \times (500 - 100) \text{K}$$

$$= 3,690,323 \text{ kJ/h}$$

#### d. Energy supplied by char from fast pyrolysis product

As can be seen in Fig.4, char is separated from pyrolysis vapor at the cyclone. The separated and collected char at Stream 9 is fed to the combustor to provide heat for the feedstock drying and pyrolysis process. The calorific value of char is 24,100 kJ/kg (adapted from wood char HHV [16] ) with the process energy requirement are 7,712,010 kJ/h plus 3,690,323 kJ/h as calculated in Energy requirement for feedstock drying and pyrolysis process (item b and c). Thus, the required amount of char to fulfill this energy requirement is estimated as follow:

$$\dot{m}(\text{char}) = \frac{(7,712,010 + 3,690,323) \text{ kJ/h}}{24,100 \text{ kJ/kg}}$$

$$= 473.13 \text{ kg/h}$$

As can be seen from Table 4 material balance, the char at stream 9 is produced at the rate of 481 kg/h, thus this amount suffice the energy required for feedstock drying and

pyrolysis process. Approximately 98% of the produced char is burned to provide the energy.

e. Energy requirement for electrostatic precipitator

Energy consumption of the ESP depends on the amount of gas pass through it. To accurately estimate the ESP power, the actual volumetric flow of gas should be measured, commonly in the unit of ACFM (actual cubic feet per minute) for blower and compressor application. Actual cubic feet per minute is the volume of gas flowing anywhere in a system independent of its density. If the system were moving air at exactly the "standard" condition, then ACFM would equal SCFM.

The current pyrolysis vapors flow at almost atmospheric pressure, thus the carrier gas flowrate at Stream 9 can be deemed as actual flow rate. By this information, the required power for ESP is estimated to be approximately 9 kW [19] which is normally the power of the induced draft fans of the ESP.

B. Production Cost

The plant is assumed to be located in Indonesia; most of the prices are heavily site-dependent especially for labor cost and electricity cost.

The production cost is influenced by the amount of bio-oil production, material cost, operational cost including labor and utility cost.

It is assume that the 100% capacity plant will be operated 300 days per year and 24 hours per day, which is equal to the availability factor of 82%. With refer to table 4 Material Balance, the following can be estimated at annual basis:

a. Feedstock requirement

$$EFB = 6,000 \frac{kg}{h} \times 24h/d \times 300d/y = 43,200,000kg/y$$

b. Bio Oil Production

$$Bio\ oil = 1,774 \frac{kg}{h} \times 24h/d \times 300d/y = 12,772,800\ kg/y$$

c. Electricity requirement for crusher and grinding

$$E_{crush} = \frac{10kWh}{ton} \times \frac{1\ ton}{1,000\ kg} \times 6,000kg/h \times 24h/d \times 300d/y = 432,000\ kWh/y$$

d. Electricity requirement for ESP

$$E_{ESP} = 9kW \times 24h/d \times 300d/y = 64,800kWh/y$$

e. Energy required for feedstock preheating and pyrolysis process

The energy required for feedstock preheating and pyrolysis can be supplied by the burning of char product. The required char to suffice this energy requirement is

almost 98% of total char production, thus it can be deemed that this required energy has been balanced by the energy provided by char. Therefore, this energy requirement no needs to be taken into account in this calculation.

f. Labor cost

It is estimated that the total labor and staff required running this plant approximately 15 persons for two shifts of operation with the annual total salary of Rp 748,000,000.

g. Maintenance cost is estimated to be Rp 200,000,000 annually.

At the present day, EFB is practically taken for granted. However, the lesson-learned from the bio-diesel derived from crude palm oil (CPO) feedstock suggests that this situation will no longer be exist once the EFB conversion to bio-oil technology has been mature and commercialized. For that reason, by taking the electricity tariff of Rp 1,115/kWh [20], the following sensitivity analysis of bio-oil production cost as a function of EFB price can be generated as shown in Fig. 5.

The other parameters have relatively minor effect on production cost of the bio-oil except for the electricity which its sensitivity at constant EFB price of Rp 100/kg shown in Fig. 6.

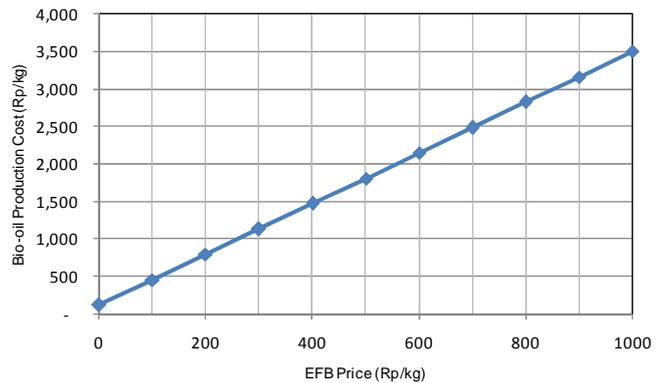


Fig. 5 Bio-Oil Production Cost as a Function of EFB Feedstock Price

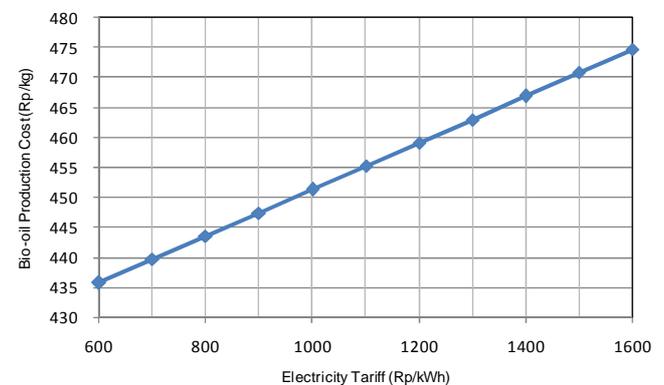


Fig. 6 Bio-Oil Production Cost as a Function of Electricity Tariff

It is apparent that feedstock price drives the production cost. Since the price of the EFB is not regulated by the government, the best option is to integrate the bio-oil plant with the palm oil plant. In this case the feedstock price can

be maintained at no cost or reduced to the lowest level. Additional benefit of integrated plant is that the electricity cost can also be reduced since normally the palm oil mill possess the excess power.

## VI. CONCLUSION

The result shows that for the current condition, the bio-oil production cost from palm empty fruit bunch seems promising to be implemented in Indonesia. The best option is to have the bio-oil plant integrated with the palm oil mill, where in this case the EFB can be kept at no cost, off the market influence. However, the more rigorous economic analysis is needed to further assess the economic potential of this biomass to liquid conversion process. One thing should be kept in mind that this technology is somewhat immature, need to be more developed and scrutinized to get a more accurate analysis result.

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