Synthesize a Sustainable Supply Chain of Biomass to Electricity via Mathematical Approach

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Abstract. The huge amount of biomass waste and palm oil mill effluent (POME) generated during oil extraction has prompted the need for a more sustainable framework in waste management. Since oil palm biomass waste is rich in lignocellulosic content, it can be potential to be converted into green energy such as bioelectricity via different pathway of processes such as the thermal conversion pathway and biochemical conversion pathway. This study proposes a mathematical approach to synthesise a sustainable supply chain of biomass to electricity by implementing the combined heat and power (CHP) system in palm oil mill. The optimum pathway of supply chain based on the technical, economical, and environmental aspects is generated. The purpose of this approach is to assist the industry players or owners to make decision in choosing the location of the pre-treatment technology, transportation method, location of power plant and configuration of CHP. A generic superstructure is first developed to achieve the objective. Then, a series of generic mathematical equations will then be formulated based on the pathways demonstrated in the generic superstructure. The mathematical equations involve general mass and energy balance, cost computation and carbon emission. The fuzzy optimisation concept will be adopted in this research to trade-off the conflicting objectives (maximize profit and minimize carbon footprint) in order to generate the optimum pathway. A palm oil-based bioelectricity supply chain case study in Selangor, Malaysia is solved to illustrate the presented approach. According to the optimised result in this case study, a total of 3,753.36 MW of bioelectricity can be generated per year. The result proved that the optimum pathway is feasible by comparing with the existing oil palm biomass-based power plant in Sarawak, where only 375 MW of electricity is generated by oil palm biomass. On the other hand, RM 7.25 million per year of net profit is estimated with a payback period of 2.81 years. Moreover, the CHP system is able to achieve 570 million kg CO₂ per year.

1. Introduction
Palm oil plant can be considered as the perfect crop for sustainable agriculture as it is able to grow in most soil condition. In addition, the palm oil extracted can be widely used in different fields after being process such as biofuel, food and pharmaceutical industries [1]. However, large amount of biomass wastes such as empty fruit bunch (EFB), palm mesocarp fibre (PMF) and palm kernel shell (PKS) will be generated while extracting the palm oil. According to Maimunah et al. [2], a total of 1.07 tons oil palm empty fruit bunch (EFB) is generated in order to extract 1 ton of palm oil. Moreover, based on Ajuboori et al. [3], Malaysia is second largest crude palm oil producer around the world. At the same time, Malaysia contributes 39% of total palm oil production of the world and 44% of world exports [3]. This leads to a generation of at least 168 million tons of biomass waste annually in Malaysia. A total of 94% of waste generated from palm oil industry is categorised as solid biomass waste [4]. The oil palm biomass waste is rich in lignocellulosic fibres namely cellulose, hemicellulose, lignin structure, rendering it a promising feedstock for production of biofuels and value-added product due to its low cost and high yield [5,6, 7, 8]. However, in current industrial practices, most of the oil palm biomass are not being recovered. These practices caused environmental issues and profit lost due to the wastage of valuable energy. Instead of just wasting the biomass, the biomass can be converted into clean energy or bioenergy via different pathways such as the thermal conversion pathway and biochemical conversion pathway. Through these pathways, the biomass can be combusted to generate heat, converted into electricity, or processed into biofuel [11].

To tackle the aforementioned issue, a feasible solution is to convert the oil palm biomass into value-added product such as heat and power. According to Onochie et al. [21], the oil palm biomass is a potential alternative to fossil fuel energy for the purpose of combustion as the oil palm biomass contain high calorific value. In this case, the combined heat and power (CHP) system is suggested to be applied in converting the biomass into heat and power as it is well-established process [9,10]. CHP system is a cogeneration system that produces heat and power from a single energy source [10]. The overall efficiency of the CHP system is appreciably higher than single power generation system [10]. Furthermore, there are several investigations that have proven the feasibility of biomass-based CHP. For instance, gasification-based CHP [12], Organic Rankine cycle-based CHP using willow chip as feedstock [12, 13] as well as, steam turbine and biomass gasification which using oil palm biomass as raw material [14]. By implementing the CHP system using palm oil biomass as feedstock, the sustainability of palm oil mill might be improved as it reduces the CO$_2$ emission and the use of fossil fuel via centralised electricity generation. However, one of the limitations to implement CHP system into current palm oil mill is the high capital cost of the CHP system. An economic evaluation has been done by Ling et al. [15], who analysed the economic performance of CHP system using oil palm biomass as the feedstock supplied from several palm oil mill. The feasibility of implementing the CHP system in palm oil biomass to bioelectricity supply chain had been considered. However, the technical and environmental performance of CHP system had not been considered in the study by Ling et al. [15]. In order to further analyse the feasibility of implementing CHP system by using oil palm biomass to bioelectricity supply chain, this study will expand the previous work by Ling et al. [15], by considering the technical and environmental performance of CHP system. A mathematical model which acts as a decision-making tool is necessary to be developed in order to analyse the feasibility of implementing CHP system in palm oil mill.

Based on Harron [22], mathematical optimisation is a highly effective prescriptive analytical method which contributes to the detection of business development difficulties as well as the efficient use of resources, applications, and services. Besides, the set of mathematical concepts and methods have been used to solve numerical and quantitative problems in various domains, such as physics, biology, engineering, economics, and business. Therefore, the mathematical model decision-making tool was created in order to synthesise optimum design of CHP system based on the requirement of the palm oil mill. The optimum design will be based on several aspects which is the technical aspect (amount of electricity generated), economic aspect (cost and profit), and environmental aspect (carbon emission).
In this study, it involves multi-objectives which is to maximise the profit and at the same time minimize the carbon footprint. However, the objectives are conflicting with each other. Therefore, fuzzy optimisation concept is adopted in this research to trade-off the conflicting objectives [16]. Henceforth, the optimum pathway of implementing CHP system in oil palm biomass to bioelectricity supply chain is selected via fuzzy-based optimisation approach in this work. The optimum design is justified by the feasibility of the CHP system in terms of technical, economic, and environmental aspects.

2. **Research Methodology**

Research methodology of this work is presented in Figure 1. As shown, a generic superstructure is first developed as shown in Figure 2. The generic superstructure demonstrates all possible pathways for the supply chain. A series of generic mathematical equations are then formulated based on the generic superstructure. The mathematical equations involve general mass and energy balance, cost computation and carbon emission. Once the general equations are developed, an industrial case study superstructure will be generated and the objectives of the case study will then be identified. Based on the objectives, the relevant data will be collected. The objectives of this case study are to obtain an optimum CHP system configuration for palm oil mill with maximum profit and minimum carbon footprint (CFP). Since, the objectives are conflicting with each other, fuzzy optimisation concept will be adopted in this case study by determining the upper and lower limit of the fuzzy-based optimisation model. A fuzzy-based mixed-integer non-linear programming (MINLP) mathematical model will be developed. The upper and lower limit of the fuzzy-based optimisation model can be determined by solving the objectives independently (maximise profit and minimum carbon footprint). These values will be substituted into the model and solved using a commercial optimisation software, LINGO 19.0.

2.1. **Generic Superstructure**

The purpose to create the generic superstructure is to formulate the generic equations which explain the supply chain that proposed in this case. Figure 2 shows the generic superstructure for the palm oil mill CHP system. Based on the generic superstructure in Figure 2, the pathway started from palm oil biomass
which generated from mill, \(m\). The biomass will then be sent to the pre-treatment, \(b\) for pre-treatment. After pre-treatment process, the intermediate product, \(c\) was produced. Next, those intermediate products will be sent to the power plant, \(t\) through a type of transportation method, \(d\). In power plant, \(t\), it consists of pre-treatment process, \(b'\) as well in order to treat the untreated biomass in mill, \(m\). Similarly, the intermediate product, \(c'\) will be generated through pre-treatment process, \(b'\). Then, the product is fed into the CHP system with configuration, \(e\) for power generation, where the product which is the electricity will be known as \(p\). A series of generic mathematical equations are formulated according to this superstructure such as general mass and energy balance, cost and profit computation and CFP computation.

![Figure 2. Generic Superstructure.](image)

### 2.2. Mass Balance Equations

As shown in Figure 2, certain amount of oil palm biomass will be produced while oil palm product was generated. Then, the oil palm biomass, \(a\) will sent for pre-treatment, \(b\). The palm oil biomass that sent to pre-treatment technology, \(b \sum_{b=1}^{B} F_{m,a,b}^{\text{Biomass Out}}\) must be less than or equal to the total biomass that generated by the plant \((F_{m,a}^{\text{Biomass Total}})\) which formulated and shown in equation (2.2.1):

\[
F_{m,a}^{\text{Biomass Total}} \geq \sum_{b=1}^{B} F_{m,a,b}^{\text{Biomass Out}} \quad \forall m \forall a \tag{2.2.1}
\]

\[
F_{m,a}^{\text{Biomass Out}} = \sum_{b=1}^{B} F_{m,a,b}^{\text{Biomass Out}} \quad \forall m \forall a \tag{2.2.2}
\]

Then, the oil palm biomass will convert into intermediate product 1, \(c\) \((F_{m,c}^{\text{Intermediate 1 in}})\) under pre-treatment process. By knowing the conversion rate \((X_{m,b,c})\), the equation of amount of intermediate product 1, \(c\) \((F_{m,c}^{\text{Intermediate 1 in}})\) was computed as equation (2.2.3):
\[ F_{m,c}^{\text{Intermediate In}} = F_{m,b}^{\text{Pre-treatment Total}} \times X_{m,b,c} \quad \forall m \forall b \forall c \quad (2.2.3) \]

Equation (2.2.4) is formulated representing the total intermediate product \( (F_{m,b,c}^{\text{Pre-treatment Out}}) \) that is produced from pre-treatment technology, \( b \).

\[ F_{m,c}^{\text{Intermediate In}} = \sum_{b=1}^{B} F_{m,b,c}^{\text{Pre-treatment Out}} \quad \forall m \forall c \quad (2.2.4) \]

\[ F_{m,d}^{\text{Pre-treatment Out}} = \sum_{c=1}^{C} F_{m,c}^{\text{Pre-treatment In}} \quad \forall m \forall d \quad (2.2.5) \]

The intermediate product is sent to power plant, \( t \) through methods of transportation, \( d \). To verify the necessary number of trips, \( n_{m,t,d}^{\text{Trip}} \) to transport the total intermediate products from mill, \( m \) to power plant, \( t \), Equation (2.2.6) is formulated, where \( Z_{\text{Transportation}} \) is the transportation capacity per trip:

\[ n_{m,t,d}^{\text{Trip}} \geq \frac{F_{m,d}^{\text{Intermediate Out}}}{Z_{\text{Transportation}}} \quad \forall m \forall t \forall d \quad (2.2.6) \]

Similarly, the intermediate products from different mill, \( m \) will sent and collected at power plant, \( t \) in transportation, \( d \) as equation (2.2.7):

\[ \sum_{t=1}^{T} F_{m,t,d}^{\text{Mill Out}} = F_{m,d}^{\text{Intermediate Out}} \quad \forall m \forall d \quad (2.2.7) \]

\[ \sum_{m=1}^{M} \sum_{d=1}^{D} F_{m,t,d}^{\text{Mill Out}} = \sum_{m=1}^{M} F_{m,d}^{\text{Power Plant In}} = F_{t}^{\text{Power Plant Total In}} \quad \forall t \quad (2.2.8) \]

After the intermediate products were transported to power plant, \( t \) from mill, \( m \). Those intermediate products will then undergo the pre-treatment process 2, \( b' \) \( (F_{t,b'}^{\text{Pre-treatment In}}) \). It can be formulated as equation (2.2.9):

\[ F_{t}^{\text{Power Plant Total In}} = \sum_{b'=1}^{B'} F_{t,b'}^{\text{Pre-treatment In}} \quad \forall t \quad (2.2.9) \]

The intermediate product after pre-treatment process 2 \( (F_{t,b'}^{\text{Pre-treatment out}}) \) will turn in to intermediate product 2 \( (F_{t,b',c'}^{\text{Intermediate In}}) \):

\[ F_{t,b'}^{\text{Pre-treatment out}} = F_{t,b'}^{\text{Pre-treatment In}} \times X_{b'} \quad \forall b' \forall t \quad (2.2.10) \]

\[ F_{t,b}^{\text{Pre-treatment out}} = \sum_{c'=1}^{C'} F_{t,b',c'}^{\text{Intermediate In}} \quad \forall b' \forall t \quad (2.2.11) \]

\[ F_{t,c'}^{\text{Intermediate In Total}} = \sum_{b'=1}^{B'} F_{t,b',c'}^{\text{Intermediate In}} \quad \forall t \forall c' \quad (2.2.12) \]
Where, $X_b$ is the conversion rate of intermediate product into intermediate product 2 ($F_{t,b,c'}^{\text{Intermediate In}}$).

The total intermediate products will then go through the CHP systems with configuration, $e$ ($F_{t,c',e}^{\text{Intermediate In Total}}$) as equation (2.2.13):

$$F_{t,c',e}^{\text{Intermediate In Total}} = F_{t,c'}^{\text{Intermediate Out Total}} \quad \forall c' \forall t$$ (2.2.13)

$$F_{t,c'}^{\text{Intermediate Out Total}} = \sum_{e=1}^{E} F_{t,c',e}^{\text{Intermediate Out}} \quad \forall c' \forall t$$ (2.2.14)

### 2.3. Economic Performance Evaluation

The economic performance evaluation for the projected CHP systems can be calculated according to the difference between total revenue and total cost. The cost of pre-treatment ($\text{TotCost}_{m}^{\text{Pre-treatment}}$) at the mill $m$, is calculated by equation (2.3.1), where $\text{Cost}_b^{\text{PreT}}$ is the cost of biomass per kilogram (MYR/kg) for pre-treatment technology, $b$:

$$\text{TotCost}_{m}^{\text{Pre-treatment}} = \sum_{b} \text{Cost}_b^{\text{PreT}} F_{m,b}^{\text{Pre-treatment In}} \quad \forall m$$ (2.3.1)

The transportation cost ($\text{TotCost}_{d}^{\text{Mill Power Plant}}$) to send the intermediate products, $c$ to power plant, $t$ can be calculated by using equation (2.3.2):

$$\text{TotCost}_{d}^{\text{Mill Power Plant}} = \sum_{t} \sum_{m} \text{Cost}_{d}^{\text{TransP}} d_{m,t}^{\text{Trip}} n_{m,t,d}^{\text{Trip}} \quad \forall d$$ (2.3.2)

Where $\text{Cost}_{d}^{\text{TransP}}$ is the cost of transportation (MYR/kg), $d_{m,t}$ is the travel distances between the mill, $m$ and power plant, $t$ while $n_{m,t,d}^{\text{Trip}}$ is the number of trips.

The cost of pre-treatment ($\text{TotCost}_{t}^{\text{Pre-treatment}}$) at power plant $t$ is determined by using equation (2.3.3), where $\text{Cost}_{b'}^{\text{PreT}}$ is the cost of biomass per kilogram (MYR/kg) for pre-treatment technology, $b'$:

$$\text{TotCost}_{t}^{\text{Pre-treatment}} = \sum_{j} \text{Cost}_{b'}^{\text{PreT}} F_{t,b'}^{\text{Pre-treatment In}} \quad \forall t$$ (2.3.3)

The total cost for CHP installation ($\text{TotCost}_{t,e}^{\text{Installation}}$) is determined based on equation (2.3.4):

$$\text{TotCost}_{t,e}^{\text{Installation}} = \text{Cost}_{e}^{\text{CHP unit}} \sum_{p=1}^{P} E\text{LEC}_{t,p}^{\text{Product}} \quad \forall e \forall t$$ (2.3.4)

Where $\text{Cost}_{e}^{\text{CHP unit}}$ is the cost for CHP configuration, $e$ per kilowatt (MYR/kW) and $E\text{LEC}_{t,p}^{\text{Product}}$ is the electricity output (kW).

The maintenance cost for CHP configuration, $e$ is calculated as equation (2.3.5), where $\text{Cost}_{e}^{\text{MainT unit}}$ is the cost for maintenance per kilowatt (MYR/kW):
\[ \text{TotCost}_{t,e}^{\text{MainT}} = \text{Cost}_{t,e}^{\text{MainT \ unit}} \sum_{p=1}^{P} \text{ELEC}_{tp}^{\text{Product}} \quad \forall e \forall t \] (2.3.5)

Equation (2.3.6) is used to calculate the energy saving revenue (\( \text{TotRV}_{tp}^{\text{Product}} \)) for CHP, where \( \text{Cost}_{p}^{\text{Elec \ unit}} \) is the energy cost per kilowatt (MYR/kW).

\[ \text{TotRV}_{q,p}^{\text{Product}} = \text{Cost}_{p}^{\text{Elec \ unit}} \text{ELEC}_{q,p}^{\text{Product}} \quad \forall p \forall q \] (2.3.6)

The net revenue for the CHP configuration \( c \) (\( \text{TotRV}_{q,e}^{\text{CHP \ system}} \)) can be determined by using equation (2.3.7):

\[ \text{TotRV}_{t,e}^{\text{CHP \ system}} = \sum_{p=1}^{P} \text{TotRV}_{tp}^{\text{Product}} - \text{TotCost}_{t,e}^{\text{MainT}} \quad \forall e \forall t \] (2.3.7)

Where \( \text{TotRV}_{tp}^{\text{Product}} \) is the total value of product \( p \) generated and \( \text{TotCost}_{t,e}^{\text{MainT}} \) is the maintenance cost for CHP configuration, \( e \).

Equation (2.3.8) is used to calculate the simple payback for investing the plant:

\[ \text{Payback} = \frac{\text{Total CHP Cost}}{\text{Net Profit}} \] (2.3.8)

2.4. Carbon Footprint (CFP) Evaluation

In order to determine the CFP of the CHP system, the carbon emission during pre-treatment processes \( b \), (\( \text{TotCFP}_{bp}^{\text{pretreatment}} \)) need to be first determined as shown in equation (2.4.1):

\[ \text{TotCFP}_{bp}^{\text{pretreatment}} = \sum_{m=1}^{M} \sum_{b=1}^{B} \text{EF}_{bp}^{\text{Power}} \text{E}_{m,b} \sum_{a=1}^{A} \text{EF}_{m,a,b}^{\text{pretreatment \ in}} \] (2.4.1)

Where, \( \text{EF}_{bp}^{\text{Power}} \) is the power generation emission factor (kg CO\(_2\)/kWh), \( \text{E}_{m,b} \) is the power consumption of pre-treatment process, \( b \) in converting palm oil biomass, \( c \) into intermediate product, \( a \) while \( \text{EF}_{m,a,b}^{\text{pretreatment \ in}} \) is the amount of palm oil biomass, \( a \) entering the pre-treatment technology, \( b \).

Similarly, the carbon emission of the pre-treatment process 2, \( b' \) (\( \text{TotCFP}_{bp'}^{\text{pretreatment}} \)) can be calculated by equation (2.4.2):

\[ \text{TotCFP}_{bp'}^{\text{pretreatment}} = \sum_{t=1}^{T} \sum_{b=1}^{B} \text{EF}_{bp'}^{\text{Power}} \text{E}_{t,b} \text{EF}_{t,b}^{\text{pretreatment \ in}} \] (2.4.2)

Therefore, the total carbon emission from pre-treatment processes (\( \text{TotCFP}_{p}^{\text{pretreatment}} \)) is determined by using equation (2.4.3):

\[ \text{TotCFP}_{p}^{\text{pretreatment}} = \text{TotCFP}_{bp}^{\text{pretreatment}} + \text{TotCFP}_{bp'}^{\text{pretreatment}} \] (2.4.3)

The carbon emission from transportation \( t \) (\( \text{TotCFP}_{t}^{\text{Mill\-CHP}} \)) is calculated in order determine to total fuel-based CFP as equation (2.4.4), where \( \text{EF}_{d}^{\text{fuel}} \) is the transportation, \( d \) emission factor (kg CO\(_2\)/km):

\[ \text{TotCFP}_{t}^{\text{Mill\-CHP}} = \text{TotCFP}_{tp}^{\text{pretreatment}} + \text{TotCFP}_{tp'}^{\text{pretreatment}} \] (2.4.4)
Thus, the total CFP from transportation is calculated as equation (2.4.5):

\[
\text{Tot}CFP_d^{Fuel,Mill,CHP} = \sum_{t=1}^{T} \sum_{m=1}^{M} EF_d^{Fuel} Z^{transportation} d_{mt} n_{m,t,d}^{Trip} \quad \forall d
\]  

(2.4.4)

The total carbon emission can be calculated using equation (2.4.6):

\[
\text{Tot}CFP = \text{Tot}CFP^{Pre}treatment + \text{Tot}CFP^{Fuel,Mill,CHP}
\]  

(2.4.5)

In contrast, the total carbon saving of each CHP configuration, \(e\) (\(CS_e\)) can be determined according to total electricity generation, as shown in equation (2.4.7):

\[
CS_{t,e} = ELEC_{t,p}^{Product} \times EF_Elec,FS \times Oph_{t,e} \quad \forall e \forall t
\]  

(2.4.7)

Where \(ELEC_e\) is the electricity generated from CHP configuration, \(e\), \(EF_Elec,FS\) is the carbon emission factor of electricity generated from fossil fuel (CO\(_2\)/kWh) and \(Oph_{t,e}\) is the operating hours of the CHP system with configuration, \(e\).

2.5. Fuzzy-Based Optimisation Approach

A fuzzy-based optimisation approach will be adopted to compute the optimum pathway for the CHP system configuration in the palm oil biomass to bioelectricity supply chain since the conflicting objectives of economic and environmental aspects. Furthermore, the fuzzy-based optimisation model combined multiple objectives into a single variable, \(\lambda\), with a range of 0 to 1. The optimum pathway is achieved by maximizing \(\lambda\). The objective function integrated into fuzzy degree of satisfaction, \(\lambda\) was shown in equation (2.5.1) and (2.5.2), where \(\text{Tot}CFP\) and \(\text{Tot}Profit\) are the total carbon footprint and net profit generated by the optimum solution. On the other hand, the \(CFP^{UL}\) and \(CFP^{LL}\) are the pre-determined upper and lower limit of carbon footprint by resolving the objective ‘minimize CFP’ independently. Similarly, \(Profit^{UL}\) and \(Profit^{LL}\) are the pre-determined by resolving the objective ‘maximize profit’ independently.

\[
\frac{CFP^{UL} - \text{Tot}CFP}{CFP^{UL} - CFP^{LL}} \geq \lambda
\]  

(2.5.1)

\[
\frac{\text{Tot}Profit - Profit^{LL}}{Profit^{UL} - Profit^{LL}} \geq \lambda
\]  

(2.5.2)

3. Case Study

Based on Figure 3, it shows the superstructure of the case study which included all the possible pathways of implementing CHP system in palm oil biomass to bioelectricity supply chain in palm oil mill. There are 3 palm oil mills were considered in this case study, which are East Palm Oil Mill (mill 1), Jugra Palm Oil Mill (mill 2) and Eng Hong Palm Oil Mill (mill 3). On the other hand, the biomass that used
to generated bioelectricity in this case study are empty fruit bunch (EFB), palm mesocarp fibre (PMF) and palm kernel shell (PKS).

![Diagram of Case Study](image)

**Figure 3.** Superstructure of Case Study.

After oil palm biomass was collected from each palm oil mill, the biomass will then feed into the steam dryer for pre-treatment process. The moisture content of the biomass will be removed during this process. Besides, the pre-treatment dryer will be placed at 2 locations, where the dryer 1 will be located at the mill itself and dryer 2 will be set at the power plant. In this case study, lorry will be the only option that can use to transport the biomass. However, the oil palm biomass can be bypassing the transportation section as well, which mean no transportation will be used to send the biomass to the power plant which is located right beside the palm oil mill. For instance, from mill 1 to power plant 1. On the other hand, there are 3 CHP configurations will be considered in this case study, that are CHP system with steam boiler (configuration 1), CHP system with biomass boiler (configuration 2) and gasifier-based biomass CHP system (configuration 3).

The data for the case study such as sago mills, efficiency of dryer and efficiency of CHP configurations is adopted from data reported by Ling et. al [15]. To conduct the economic and environmental evaluations, the emission factor of transportation, the efficiency of dryer, $b$ and various CHP systems, $e$ are estimated from literature as summarized in Table 1 [15, 17, 18].
### Table 1. Tabulation Data of Case Study Data [15, 17, 18].

| Feed Type | Product Type | Conversion (product/feed) | Cost (RM) | CFP (kg CO₂/kg feed) |
|-----------|--------------|---------------------------|-----------|----------------------|
| Lorry     | EFB          | EFB                       | -         | 2.72 RM/km           | 0.95000 kg CO₂/km |
|           | PMF          | PMF                       |           |                      |                    |
|           | PKS          | PKS                       |           |                      |                    |
| Dryer     | EFB          | Treated Biomass           | 0.8593    | 689.93 RM/kg feed    | 0.08998            |
|           | PMF          | Treated Biomass           | 0.8672    |                      |                    |
|           | PKS          |                            | 0.7500    |                      |                    |
| CHP 1     | Treated     | Power (kW)                | 0.4000    | 3,114,880.00         | 0.00000            |
| (Configuration 1) | Biomass    |                           |           |                      |                    |
| CHP 2     | Treated     | Power (kW)                | 0.4890    | 7,952,640.00         | 0.00000            |
| (Configuration 2) | Biomass    |                           |           |                      |                    |
| CHP 3     | Treated     |                           | 0.3700    | 17,288,960.00        | 0.00000            |
| (Configuration 3) | Biomass    |                           |           |                      |                    |

### 3.1. Result and Discussion

Table 2 shows the upper and lower fuzzy limit of the individual objective in this case study which is the maximum profit and minimum CFP. The upper and lower limits were pre-determined in order to obtain the optimum pathway by coding those result into the Mixed Integer Non-Linear Programming (MINLP) model via Lingo 19.0.

### Table 2. Objective Functions for Profit and CFP.

| Objective Functions | Profit (mil RM/year) | CFP (tonne CO₂/year) |
|---------------------|----------------------|----------------------|
| Max Profit          | 9.99                 | 3821.6               |
| Min CFP             | 5.98                 | 3512.3               |

Table 3 is the data of profit and CFP for optimum pathway. Both economic and environmental aspects were satisfied at the same time in the optimum pathway of the palm oil biomass to electricity supply chain was determined and shown in Figure 4. Based on the superstructure of optimum pathways, the oil palm biomass for all palm oil mill needed to undergo pre-treatment process on-site before the biomass sent to the power plant by using lorry as the transportation. However, some of the pre-treated palm oil biomass will be bypassed from palm oil mill 3 to power plant 3, where the power plant 3 is located right beside the palm oil mill 3. Note that the selected configurations of the power plant are power plant 2 and power plant 3. On the other hand, the CHP system with steam boiler (configuration 1) was chosen as the optimum CHP system to generate bioelectricity in power plant 2, while the pre-treated palm oil biomass which entering power plant 3 will be converted into bioelectricity through the gasifier-based biomass CHP system (configuration 3). Moreover, power plant 1 is not required to achieve the optimisation objectives according to the obtained result. The summary of optimum pathway of the palm oil biomass to electricity supply chain was tabulated and shown in Table 4 and Table 5.

### Table 3. Tabulation Data of Profit and CFP for Optimum Pathway.

| Profit (mil RM/year) | CFP (tonne CO₂/year) |
|----------------------|----------------------|
| 7.25                 | 3,674.35             |
Figure 4. Superstructure of Optimum Pathways

Table 4. Summary of Optimum Pathway of Oil Palm Biomass to Electricity Supply Chain.

| Network Configuration | No. of CHP | Total Amount of Electricity Generated | Net Profit/year |
|------------------------|-----------|--------------------------------------|-----------------|
| : Centralized          | : 2       | : 4,207.81 MW/year                   | : RM 7.25 million/year |

| Mill Location | Pre-treatment Location | Transportation Method | Power Plant | CHP Configuration |
|---------------|------------------------|-----------------------|--------------|-------------------|
| Mill 1        | Mill 1                 | Lorry                 | Power Plant 2 | E1                |
|               |                        |                       | Power Plant 3 | E3                |
| Mill 2        | Mill 2                 | Bypass                | Power Plant 2 | E1                |
|               |                        |                       | Power Plant 3 | E3                |
| Mill 3        | Mill 3                 | Lorry                 | Power Plant 2 | E1                |
|               |                        |                       | Power Plant 3 | E3                |

Table 5. Total Amount of Electricity Generated of Optimum CHP System Configuration.

| CHP Configuration | Electricity Generated (MW/year) |
|-------------------|---------------------------------|
| E1                | 507,803.7                       |
| E3                | 3,700,006.3                     |
### Technical and Environmental Performance Evaluation

Table 6 shows the summary of the technical evaluation. In order to access the technical and environmental performance of the optimum pathway of the oil palm biomass to electricity supply chain, the total electricity generated in one year and the net carbon saving are required to be analyzed. According to Table 6, the optimum CHP system required to consume a total amount of 21.697 million kg of oil palm biomass per year in order to generate 4,207.81 MW of electricity per year. On the other hand, the net electricity generated by this optimum pathway is approximate to 3,753.36 MW per year by deducting the electricity usage of the pre-treatment process and the CHP system from the total electricity generated, which is 191.02 MW per year and 263.53 MW per year, respectively. The results proved that the pathway is sufficient by comparing with the existing palm oil biomass-based power plant in Sarawak, where only around 375 MW of electricity is contributed to by oil palm biomass [20]. Besides, it is suggested to sell the remaining electricity to the grid or supply the bioelectricity to the nearby household in order to increase the economic and environmental performance.

| Technical Aspects              | Values                      |
|--------------------------------|-----------------------------|
| Total Biomass Feed             | 21.697 mil kg/year          |
| Total Electricity Generated    | 4,207.81 MW/year            |
| Electricity Usage of Pre-treatment Technology | 191.02 MW/year |
| Electricity Usage of CHP       | 263.53 MW/year              |
| Net Electricity Generation     | 3753.36 MW/year             |

Furthermore, the data of the summary of environmental evaluation was tabulated and shown in Table 7. The total amount of net electricity by the system can be used to determine the carbon saving. Based on the results obtained by the model, it shows that around 1.56 million kg of CO₂ was saved per day, which equivalent to 570 million kg of CO₂ was saved per year. It is also equivalent to 15% of total carbon emissions of 3,700 million kg CO₂ of Malaysia in year 2017 [19].

| Environmental Aspects          | Values                      |
|--------------------------------|-----------------------------|
| Total Amount of Green Electricity Produced | 3,753.36 MW/year |
| Total Carbon Saving            | 570 mil kgCO₂/year         |
| Total Carbon Emission in Malaysia in year 2017 | 3,700 mil kgCO₂/year |

### Economic Performance Evaluation

Table 8 illustrates that the summary of economic evaluation. The simple payback was analysed according to the net profit of the system which computed by the model in order to evaluate the economic performance of the system. The cash flow per year was assumed evenly as there is not much information to investigate the annual payback for the plant. Based on the result obtained by the model, the payback of the optimum pathway of the palm oil biomass to electricity supply chain is 2.81 year.

| Economical Aspects             | RM             |
|--------------------------------|----------------|
| Cost of CHP E1                 | 3.1149 mil     |
| Cost of CHP E3                 | 17.289 mil     |
| Total CHP Cost                 | 20.4039 mil    |
| Revenue from Electricity Produced | 14.035 mil/year |
| Pre-treatment Process Cost     | 0.4721 mil/year|
| Transportation Cost            | 0.628 mil/year |
| CHP Operation Cost             | 4.84 mil/year  |
| Labour Cost                    | 1.3824 mil/year|
| Net Profit                     | 7.25 mil/year  |
### 3.1.3. Discussion

In Tables 9 to 12, the mass flowrates that obtained between different objective functions are listed. Table 9 listed the mass flowrates of oil palm biomass to plant plants for different objective functions. For the objective of maximising net profit, all the oil palm biomass was sent to power plant 3, it is because power plant 3 is located at the center of the other two palm oil mill. By sending the biomass to power plant 3, the transportation cost is reduced since the distance is shorter. For objective of minimizing the CFP, the oil palm biomass will be bypassed from each mill to the power plant which is located beside the mill in order to reduce the number of trips of the transportation. For maximising $\lambda$, the model has computed an optimum pathway, where both objectives were satisfied.

Table 10 listed the selection of CHP configuration for different objective functions. All the oil palm biomass was entering CHP configuration 1 for minimising CFP while producing electricity. On the other hand, all the oil palm biomass is sent to CHP configuration 3 for maximising the profit as its conversion rate is the highest compared to the other configurations. With higher conversion rate, that signifies more electricity can be produced which subsequently increases the profit. For maximising $\lambda$, the model computed an optimum pathway, where most of the oil palm biomass is sent to CHP configuration 3 while some of the biomass will be sent to CHP configuration 1 as it has the lowest capital cost compared to CHP configuration 2 and 3.

| Table 9. Mass Flowrates of Oil Palm Biomass to Plant Plants for Different Objective Functions. |
|---|---|---|---|
| Flow rate from palm oil mill to power plant (kg/day) | Maximize $\text{TotProfit}^{\text{net}}$ | | |
| | Power Plant 1 | Power Plant 2 | Power Plant 3 |
| Mill 1 | 0.00 | 0.00 | 21,895.98 |
| Mill 2 | 0.00 | 0.00 | 29,487.01 |
| Mill 3 | 0.00 | 0.00 | 29,487.01 |
| Minimize $\text{TotCFP}^{\text{net}}$ | | | |
| Power Plant 1 | Power Plant 2 | Power Plant 3 |
| Mill 1 | 20,469.40 | 0.00 | 0.00 |
| Mill 2 | 0.00 | 19,508.64 | 0.00 |
| Mill 3 | 0.00 | 0.00 | 19,464.40 |
| Maximize $\lambda$ | | | |
| Power Plant 1 | Power Plant 2 | Power Plant 3 |
| Mill 1 | 0.00 | 10,874.09 | 9,595.31 |
| Mill 2 | 0.00 | 3,198.44 | 16,310.20 |
| Mill 3 | 0.00 | 0.00 | 19,464.99 |

| Table 10. Mass Flowrates of Treated Oil Palm Biomass to CHP Configuration. |
|---|---|---|---|---|---|---|---|---|
| Power Plants | Minimize $\text{TotCFP}^{\text{net}}$ | Maximize $\text{TotProfit}^{\text{net}}$ | Maximize $\lambda$ |
| | E1 | E2 | E3 | E1 | E2 | E3 | E1 | E2 | E3 |
| T1 | 20469.403 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| T2 | 19508.638 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 14.072.53 | 0.00 | 0.00 |
| T3 | 19464.403 | 0.00 | 0.00 | 0.00 | 0.00 | 59.443.03 | 0.00 | 0.00 | 45.370.50 |

Note: E1, E2, E3 is representing CHP configuration; T1, T2, T3 is representing the Power Plant.

Table 11 states the mass flowrates of oil palm biomass to pre-treatment process location. In this case study, the pre-treatment process is affecting the CFP of significantly. When the objective is to minimise the CFP, all biomass is suggested to pre-treat on site before sending it for power generation in order to lower the amount by transportation so that the CFP generated through transportation will be minimized subsequently. In order to maximise the profit of the case study, oil palm biomass is best to be pre-treated...
off-site, at the power plant 3, T3. With this arrangement, the amount of dryer required in the pathway is reduced when oil palm biomass is pretreated at the centralised pre-treatment process. Henceforth, it is able to improve the performance in economic aspects. For maximising $\lambda$, the model computed an optimum pathway, where both objectives were satisfied.

Similarly, the transportation method affects CFP and total profit in this case study. By referring to Table 12, in order to minimise CFP, all the oil palm biomass will be bypassed to the power plant located beside each mill without using any transportation means. When maximising total profit is the aim, most of the oil palm biomass will be transported to power plant 3. The biomass from mill 3 bypassed to power plant T3 reduces the transportation cost. Besides, its ability to generate more electricity has also placed this combination at a good economic standing. To satisfy both objectives on minimising CFP and maximizing total profit, the model has computed an optimum pathway to maximise $\lambda$ as stated in Table 12.

| Location | Dryer | Minimise $\text{TotCFP}_\text{net}$ | Maximise $\text{TotalProfit}_\text{net}$ | Maximize $\lambda$ |
|----------|-------|---------------------------------|---------------------------------|---------------|
|          | EFB   | PMF    | PKS    | EFB   | PMF    | PKS    | EFB   | PMF    | PKS    |
| Mill 1   |       |        |        |       |        |        |       |        |        |
|          | 10,790| 7,100  | 2,580  | 0     | 0      | 0      | 10,790| 7,100  | 2,580  |
| Mill 2   |       |        |        |       |        |        |       |        |        |
|          | 12,140| 7,900  | 2,910  | 0     | 0      | 0      | 12,140| 7,900  | 2,910  |
| Mill 3   |       |        |        |       |        |        |       |        |        |
| T1       | 0     | 0      | 0      | 0     | 0      | 0      | 0     | 0      | 0      |
| T2       | 0     | 0      | 0      | 0     | 0      | 0      | 0     | 0      | 0      |
| T3       | 0     | 0      | 0      | 35,070| 22,900 | 22,900 | 0     | 0      | 0      |

| Location | Minimise $\text{TotCFP}_\text{net}$ | Maximise $\text{TotalProfit}_\text{net}$ | Maximize $\lambda$ |
|----------|---------------------------------|---------------------------------|---------------|
|          | Lorry   | Bypass | Lorry   | Bypass | Lorry   | Bypass |
| Mill 1   | 0       | 20,469.40 | 21,895.98 | 0.00 | 20,469.40 | 0.00 |
| Mill 2   | 0       | 19,508.64 | 29,487.01 | 0.00 | 16,310.20 | 3,198.44 |
| Mill 3   | 0       | 19,464.40 | 0.00 | 29,487.01 | 0.00 | 19,464.99 |

4. Conclusions
In this work, a mathematical approach was proposed to synthesise a sustainable supply chain of biomass to electricity by implementing the CHP system in palm oil mill. The optimum pathway of supply chain based on the technical, economical, and environmental aspects was generated. The purpose of this approach is to assists the industry players or owners to make decision in choosing the location of the pre-treatment technology, transportation method, location of power plant and configuration of CHP. Based on the results obtained, the selected pathway of CHP system is a centralized and decentralized system, where centralized CHP system is placed at power plant 3 and decentralized CHP system located at power plant 2. The capacity of feed for power plant 2 and 3 is 14,072.53 kg and 45,370.50 kg per day, respectively. On the other hand, the biomass pre-treatment process will be carried out at the palm oil mill before sending it to the respective power plant. The centralised CHP system able to generate approximate 3,700,006.3 MW of bioelectricity per year, while the decentralized CHP system was expected to generate 507,803.70 MW of bioelectricity per year as well. Therefore, net total electricity that generated by the optimum pathway is around 3,753.36 MW per year with a net profit of RM 7.25 million per year and the simple payback of 2.81 years. The proposed approach can be further extended to include the electricity substation and workplace footprint.

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