A Superstructure Based Enviro-Economic Optimization for Production Strategy of Oil Palm Derivatives

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Abstract. Indonesia is one of the largest palm oil producers in the world. Palm oil has a wide range of derivative products that have higher values than in the upstream oil palm products. Indonesia still exports mostly crude palm oil rather than its derivatives. The objective of this research is to obtain the best strategy of developing downstream palm oil industry by considering the total price and greenhouse gas emission. Economic objective function is the total selling price of all products and environmental objective measured by the total greenhouse gas emissions. Multi-objective optimization is based on State-Task Network superstructure with fixed variable of product selling price, emission factor, conversion factor, national demand and global demand of the products. Multi-objective optimization is carried out using GAMS with Cplex 12.6.3 solver. The total selling price obtained amounted to 51.67 billion USD and total GHG emissions generated were 88.05 million tons CO\textsubscript{2}e. The selected production pathway is the production of 54 palm oil derivatives products to meet domestic needs and 21 of them can be exported (1 FFB derivative product, 4 CPO derivative products, 1 POME derivative product, 4 EFB derivative products, 2 PKS derivative products, and 9 Palm Kernel derivative products).

1. Introduction

Indonesia produces more than a half of world Crude Palm Oil (CPO) demand, correspond to 31.8 million ton of CPO [1]. 25.1 million tons of it is exported, consisting of 7 million ton of CPO; 15.57 million ton of refined CPO; and 2.43 million tons of lauric acid, biodiesel and oleo chemicals. Almost 80% of total palm oil produced are exported in the form of CPO and refined CPO, which are low value-added products. The prices of crude products are consistently the most volatile rather than finished goods. To sustain the long-term development of the palm oil industry, the development strategy should move from production of low to high value added of products by processing CPO and unused palm oil waste to the derivative products [2]. Thus, Indonesia needs to accelerate the development of downstream palm oil industry by considering simultaneously economic and environmental aspects. In a palm oil processing, only 25-30% of the product is yielded, the remaining 70-75% is residue from waste of the processing such as: empty fruit bunch (EFB), palm oil mill effluent (POME), palm mesocarp fiber (PMF), palm kernel shell (PKS), and palm fatty acid distillates (PFAD) [3]. Currently, palm oil waste is only used as fertilizer or end up in landfills. To maximize palm oil value chain, the wastes can be reused to yield higher selling value of commodities [4]. The development of downstream palm oil industry is also affected by external factors, such as EU anti-dumping tariff for Indonesia's biodiesel, and Renewable Energy Directive (RED) to ban the use of
vegetable oils and CPO from Indonesia as a feedstock of biofuels by 2020 because of deforestation issues [5]. It can disrupt exports of 3.2 million tons per year of palm oil product to the EU.

Several studies related to this research have been conducted. Egieya et al. have developed biogas supply-chain optimization with Mixed-Integer Linear Programming (MILP) [6]. Tian and You and Ng et al. have proposed a hierarchical approach optimization [7, 8]. Andiappan et al. have proposed multi-objective optimization of integrated biorefinery with various biomass conversion system [9]. Abdulrazik et al. and Murillo-Alvarado et al. have done economic and environmental objective optimization using superstructure to obtain the most optimal production pathway [10, 11]. Abdulrazik et al. proposed superstructure optimization for only the derivative products of oil palm empty fruit bunches in Malaysia, but the environmental aspects are quantified into emission costs so optimization is done only with single objective function of maximizing profits [10]. Murillo-Alvarado et al. carried out a multi-objective optimization by maximizing net profit and minimizing environmental impact to find the best production pathway of bio-refinery in Mexico with a choice of various biomass, process and products [11].

With regard to the need of innovative strategy for developing Indonesia’s downstream palm oil industry, the aim of this study is to develop the strategies for production of downstream oil palm industry in supporting the decision maker’s objectives that is a trade-off between maximizing selling prices of products and minimizing greenhouse gas emissions.

2. Methods

The research method consists of 2 main steps, the first one is the formation of superstructure, and the second one is the multi-objective optimization calculation. The main assumptions for this research are for number process and raw material variation, a raw material can only produce one type of product with one specific process; technical consideration is limited to conversion factor; economical consideration is selling price of products; environmental consideration is greenhouse gas (GHG) emission of CO₂, N₂O, CH₄, HFCs, PFCs and SF₆ taken from Life Cycle Assessment (LCA) method; the current installed capacity of palm oil products in Indonesia will not be considered on analysis but only as a benchmark; the amount of fresh fruit bunch or fresh oil palm fruit (FFB) is estimated from CPO production.

2.1. Formation of Superstructure

Nuh and Nasir have provided ways to specify and connect all potential raw materials and products across several series of tasks, i.e., operating units and or process units such as converting raw materials into products [12]. In this study, the superstructure is built in the State-Task-Network superstructure representation approach. Quaglia et al. have presented the way to design a superstructure representation by alternative collection method [13]. Pham and El-Halwagi (2012) has developed the merging process with forward and backward synthesis [14]. The superstructure made starting from FFB then generated CPO, POME, EFB, palm kernel shell and palm kernel. After that, superstructure developed for each of these raw feedstocks.

There are no variation of raw materials and production processes, in the sense that one type of product is produced from one type of raw material with one type of process. The superstructure obtained is shown on Figure 1. The oval shape describes the process for producing a product from a previous biomass. The colour difference denotes the difference in raw materials (FFB) (g), raw feedstock (i), intermediate 1 (k), intermediate 2 (m) and end products (o). Green indicates the main raw material, light yellow indicates raw feedstock, orange indicates intermediate 1, blue denotes intermediate 2, and red signifies the final product. (h) denotes the crude feedstock production process, (j) denotes the intermediate production process 1, (l) denotes the intermediate production process 2 and (n) signifies the production process of the final product. Each product is given a vertical notation of numbers to distinguish one product from another on the same column.
2.2. Mathematical Model

The objective functions of this research are to maximize the total selling price of the product and minimize total GHG emissions. Sales of the products times the products price will result to total selling price. A sale of the products is number of produced products reduced by number of products to be processed further. The number of products produced equals to amount of raw material times conversion factor. Total emission as the other objective function equals to amount of produced products times emission factor. Amount of FFB to be processed must be less or equal to amount of FFB available in Indonesia. The amount of FFB available in Indonesia is 155.3 million tons. Amount of sold products must be in between national demand and the global demand of the products. Here are the mathematical models. Table 1 describes the description of the terms.
Maximizing Total Selling Price = Max (TOTALPRICE) \hspace{1cm} (1)

Minimizing Total Emission = Min (TOTALEMISSION) \hspace{1cm} (2)

\[ GD \geq \sum_{i=1}^{5} S_i + \sum_{k=1}^{18} S_k + \sum_{m=1}^{19} S_m + \sum_{o=1}^{14} S_o \geq ND \hspace{1cm} (3) \]

\[ TOTALPRICE = \sum_{i=1}^{5} S_i \cdot P_i + \sum_{k=1}^{18} S_k \cdot P_k + \sum_{m=1}^{19} S_m \cdot P_m + \sum_{o=1}^{14} S_o \cdot P_o \hspace{1cm} (4) \]

\[ S_i = P_i - \sum_{k=1}^{18} R_{i,k} \hspace{1cm} (5) \]

\[ S_k = P_k - \sum_{m=1}^{19} R_{k,m} \hspace{1cm} (6) \]

\[ S_m = P_m - \sum_{o=1}^{14} R_{m,o} \hspace{1cm} (7) \]

\[ S_o = P_o \hspace{1cm} (8) \]

\[ \sum_{i=1}^{5} R_{g,i} \leq O_g \hspace{1cm} (9) \]

\[ P_i = R_{g,i} \cdot CV_{g,i} \hspace{1cm} (10) \]

\[ P_k = R_{i,k} \cdot CV_{i,k} \hspace{1cm} (11) \]

\[ P_m = R_{k,m} \cdot CV_{k,m} \hspace{1cm} (12) \]

\[ P_o = R_{m,o} \cdot CV_{m,o} \hspace{1cm} (13) \]

\[ TOTALEMISSION = \left[ \left( \sum_{i=1}^{5} PE_i \right) + \left( \sum_{k=1}^{18} PE_k \right) + \left( \sum_{m=1}^{19} PE_m \right) + \left( \sum_{o=1}^{14} PE_o \right) \right] \hspace{1cm} (14) \]

\[ PE_i = P_i \cdot EF_{g,i} \hspace{1cm} (15) \]

\[ PE_k = P_k \cdot EF_{i,k} \hspace{1cm} (16) \]

\[ PE_m = P_m \cdot EF_{k,m} \hspace{1cm} (17) \]

\[ PE_o = P_o \cdot EF_{m,o} \hspace{1cm} (18) \]

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
\textbf{Term} & \textbf{Category} & \textbf{Description} \\
\hline
\textit{TOTALPRICE} & Variable & The total selling price of all products per year in USD \\
\hline
\textit{TOTALEMISSION} & Variable & The total amount of greenhouse gas emissions produced in tons of CO\textsubscript{2}e \\
\hline
\textit{Og} & Parameter & Number of Fresh Fruit Bunch in Indonesia that can be further processed in tons per year \\
\hline
\textit{S}_i & Variable & Amount of the (i) products sold directly in tons per year \\
\hline
\textit{S}_k & Variable & Amount of the (k) products sold directly in tons per year \\
\hline
\textit{S}_m & Variable & Amount of the (m) products sold directly in tons per year \\
\hline
\textit{S}_o & Variable & Amount of the (o) products sold directly in tons per year \\
\hline
\textit{P}_i & Variable & Amount of (i) products generated in tons per year \\
\hline
\textit{P}_k & Variable & Amount of (k) products generated in tons per year \\
\hline
\textit{P}_m & Variable & Amount of (m) products generated in tons per year \\
\hline
\textit{P}_o & Variable & Amount of (o) products generated in tons per year \\
\hline
\textit{PE}_i & Variable & The amount of emissions generated from the production of (i) at tons of CO\textsubscript{2} is equivalent / year \\
\hline
\textit{PE}_k & Variable & The amount of emissions generated from the production of (k) at tons of CO\textsubscript{2} is equivalent / year \\
\hline
\textit{PE}_m & Variable & The amount of emissions generated from the production of \\
\hline
\end{tabular}
\caption{Description of the Terms}
\end{table}
(m) at tons of CO₂ is equivalent / year

PE₀ Variable The amount of emissions generated from the production of (o) at tons of CO₂ is equivalent / year

Rg,i Variable The amount of product (g) to be processed further for production of (i) in tons per year

R⁻ The amount of product (i) to be processed further for production of (k) in tons per year

Rk,m Variable The amount of product (k) to be processed further for production of (m) in tons per year

Rm,o Variable The amount of product (m) to be processed further for production of (o) in tons per year

ND Parameter Domestic demand of products (i), (k), (m), and (o) in tons

GD Parameter Global demand of products (i), (k), (m), and (o) in tons

CVg,i Parameter The conversion factor for generating (i) from (g)

CV⁻ Parameter The conversion factor for generating (k) from (i)

CVk,m Parameter The conversion factor for generating (m) from (k)

CVm,o Parameter The conversion factor for generating (o) from (m)

EFg,i Parameter The CO₂ emission factor for production (i) of (g) in tons CO₂e

EF⁻ Parameter The CO₂ emission factor for production (k) of (i) in tons CO₂e

EFk,m Parameter The CO₂ emission factor for production (m) of (k) in tons CO₂e

EFm,o Parameter The CO₂ emission factor for production (o) of (m) in tons CO₂e

Pr_i Parameter The selling price of the product (i) in USD per ton

Pr_k Parameter The selling price of the product (k) in USD per ton

Pr_m Parameter The selling price of the product (m) in USD per ton

Pr_o Parameter The selling price of the product (o) in USD per ton

Multi objective optimization is done by ε-constraint method. The objective function that will be maintained is maximizing the total selling price, so the objective function of minimizing total emissions will be modified into constraints using the following linear equations:

\[ f_{2\text{limit}} = (f_{1} - f_{1\text{max}f_{1}}) \frac{w_{1}(f_{2\text{max}f_{1}} - f_{2\text{min}f_{2}})}{w_{2}(f_{1\text{min}f_{2}} - f_{1\text{max}f_{1}})} + f_{2\text{min}f_{2}} \]  

(19)

\( f_{1\text{max}f_{1}} \) shows \( f_{1} \) that has been obtained with maximizing \( f_{1} \) when only maximizing the total selling price. \( f_{1\text{min}f_{2}} \) shows \( f_{1} \) that has been obtained with minimizing \( f_{2} \) when only minimizing total emissions.

The mathematical models then are performed by GAMS with Cplex 12.6.3 solver for MILP problems. The analysis is started on analysing the production pathway when maximum total price is obtained, and then analyse the production pathway when minimum total emission is obtained. The generated Pareto curve and the production pathway of its trade-off point will be analysed. Sensitivity analysis based on the recent global issue also will be conducted.

3. Results and Discussions

3.1. Maximizing Total Price

In case of maximizing the selling price as an objective, the total selling price obtained is 55.6 billion USD and total emission of 91.1 million tons of CO₂e. The number of FFBs available in Indonesia is
assumed to be 155.3 million tons, resulting from Indonesia's CPO production figures in 2017 of 31.07 million tons for the yield of CPO from FFB which is 0.2. The amount of FFB processed is as much as FFB available in Indonesia. It shows that it takes all available FFBs to get the maximum selling price possible. Figure 2 describes the potential production pathways of palm oil derivatives for case of maximizing of the total selling price. The products are differentiated in categories products that have already been produced in Indonesia from palm oil as raw materials which are marked in yellow, and which have not been produced in Indonesia in red. There are two types of production pathways, namely the selected path based on the optimization with a straight line, and which are not selected with the dashed line. The products exported are marked with blue box.

![Figure 2. Production Pathway of Oil Palm Derivatives for Maximizing Total Price](image)

All of the derivative products are produced, except beta carotene and single cell protein. So, there are 54 derivative products that are produced to fulfil domestic demands. There are 21 products...
exported. Most of the products that are exported are the third ($m$) and fourth ($o$) derivative products of FFB. 1 FFB derivative product (POME), 1 POME derivative product (compost), 2 EFB derivative products (cellulose and activated carbon), 1 palm kernel derivative product (Palm Kernel Expeller or PKE), 2 Refined Bleached Deodorized Palm Oil (RBDPO) derivative products (Refined Bleached Deodorized Palm Oil Olein/RBDPOL and Refined Bleached Deodorized Palm Oil Stearin/RBDPS), 1 glycerine derivative product (acrolein), 2 cellulose derivative products (Carboxymethyl cellulose/CMC and glucose), 1 torrefied pellet derivative product (bio-oil), 6 CPKO derivative products (all of the fatty acids except stearic acid), 2 RBDPOL derivative products (double olein and Palm Mid Fraction/PMF) and 2 Refined Bleached Deodorized Palm Kernel Oil (RBDPKO) derivative products (Refined Bleached Deodorized Palm Kernel Stearin/RBDPKS and Hydrogenated Palm Kernel Oil/HPKO). This is because third and fourth derivative products provide maximum value increase compared to first or second derivative products as they go through more processes.

In $i$ products production, only POME is exported. In production of $k$ products, beta carotene did not get any supply of raw materials, due to the very small conversion factor (0.0001) and therefore it is not optimal to produce. Same goes for Single Cell Protein (SCP), because other product demand is much higher than SCP and the selling price of SCP is not too high (650 USD per ton). PKE is produced at 4.4 million tons and should all be sold because it does not have any derivative products. Activated carbon and cellulose are produced for directly sold and meet global demand. It indicates that these products can provide the maximum value increase compared to production of other $k$ products. The other products give more maximum selling price if it becomes raw material for production of next derivative products. In production of $m$ products such as, RBDPOL, RBDPS, acrolein, CMC, bio-oil and almost all fatty acids are exported. RBDPOL and RBDPS are mostly sold directly, although they have derivative products that can increase the selling price. RBDPOL and RBDPS are produced 18.4 million tons and 4.6 million tons, respectively. Both have high global demand (53.4 million for RBDPOL, and 13.4 million for RBDPS). Double olein, PMF and mid stearin as their derivatives have higher selling prices, but global demand for these three products does not exceed 130 thousand tons each. CMC and acrolein are exported, because of having a much higher selling price than its raw material. Glucose is exported because its derivative products have a lower selling price than glucose. Only stearic acid is not exported because stearic acid has the lowest conversion factor compared to other fatty acids in the same process. Production of $o$ products is to meet the national demand. Double olein, PMF and HPKO are exported to provide an optimal selling price.

3.2. Minimizing Total Emission
For the least total emission, the total selling price reached is 30.35 billion USD and total emission of 87.3 million tons CO$_2$e. The number of FFBs processed in the system is 155.2 million tons. In this case of the production meet only for domestic demand. It is seen that the number of FFBs processed is about 99% of the total FFB available in Indonesia. Figure 3 describes the potential production pathways of palm oil derivatives for case of minimizing total emission.
Figure 3. Production Pathway of Oil Palm Derivatives for Minimizing Total Emission

All of the derivative products except beta carotene and single cell protein (54 derivative products) are produced to fulfill national demands. The number of products that are exported is 16 products. It consists of 7 products of first (i) and second (k) palm oil derivatives, and 8 products of the third (m) and fourth (o) derivatives. 1 FFB derivative product (POME), 1 CPO derivative product (RBDPO), 1 POME derivative product (compost), 1 EFB derivative product (Dried Long Fibre/DLF), 1 PKS derivative product (torrefied pellet), 2 palm kernel derivative products (PKE and CPKO), 1 RBDPO derivative product (RBDPS), 1 torrefied pellet derivative product (bio-oil), 6 CPKO derivative products (all of the fatty acids except stearic acid), and 1 RBDPKO derivative product (RBDPKS).

The production of i products, POME is converted to the compost and electricity that required 913.11 million tons of POME for total POME production of 93.12 million tons, so POME should be sold to meet global needs. The exported k products are RBDPO, compost, torrefied pellet, CPKO and PKE. RBDPO is exported due to its high production. Compost is exported to utilize the available...
POME. DLF is exported as it is produced in large quantities because of its lowest emission factor compared to the other EFB’s derivatives with 0.0041. Same goes for torrefied pellet. CPKO and PKE are exported to minimize the emission of further processing it. Exported m products are RBDPS, bio-oil and all fatty acids except stearic acid. Bio-oil produces less emission than further processed for bio-gasoline production which has a production emission factor of 13 tons CO₂e/ton. On ò product production, all are produced to meet domestic needs, except for RBDPKS that produced in the same process as RBDPKOL.

3.3. Pareto Curve Analysis
Figure 4 shows the Pareto-optimal curves generated from multi-objective optimization with weighted variations between total selling prices and total emissions.

![Figure 4. Pareto curve of multi-objective optimization](image)

It can be seen that there is a trade-off point where the weighting between the emissions and the total selling price is at its most optimal. The trade-off point occurs in the weighting of 55% of total selling price and 45% of total emissions. The total selling price generated is 51.68 billion USD and total emissions generated are 88.05 million tons CO₂e at the trade-off point.

Emissions generated from production on the minimum total emission calculation and at the point of trade-off are relatively insignificant, only rising around 600 thousand tons of CO₂e to increase the total selling price to nearly 20 billion USD. The increase in emissions from both points is largely due to the emissions generated in RBDPOL production which increased from 35 thousand tons of CO₂e to 152 thousand tons of CO₂e. The significant increase in selling prices was influenced by cellulose sales which increased from 100 thousand USD to 11.5 billion USD, hemicellulose from 236 thousand USD to 1.9 billion USD, activated carbon from 26 thousand USD to 3 billion USD and RBDPOL of 3.2 billion USD to 13.6 billion USD.

The main emissions from production on the maximum total selling price calculation come from bio-oil production with emissions of 2.5 million tons CO₂e, rising considerably from the trade-off point with 52.5 thousand tons CO₂e emissions. In addition, emissions from glucose production increased from 22 tons CO₂e to 147 thousand tons of CO₂e and HPKO from 185 tons CO₂e to 186 thousand tons CO₂e. The increase in the selling price of the products is not significant. At the point of selling price optimization, the increase occurred for the sale of Bio-oil from 63 million USD to 3.1 billion USD, glucose from 86 thousand USD to 2.9 billion USD and HPKO from 2 million USD to 2.1 billion USD. However, the reduction also occurred significantly on CPKO sales which decreased from 3.5 billion USD to only 282 million USD, torrefied pellet from 1 billion USD to only 88 thousand USD and hemicellulose from 1.9 billion USD to only 240 thousand USD.

Figure 5 shows the production pathways of palm oil derivatives with multi-objective optimization.
Figure 5. Production Pathway of Oil Palm Derivative Products for Multi-Objective

At the trade-off, the available EFB is not allocated to produce DLF. EFB is allocated to produce products that have higher selling prices such as cellulose and hemicellulose which have a selling price of 1.98 thousand USD and 1.8 thousand USD per ton, much higher than DLF with 134.9 USD per ton. Activated carbon is also produced more at the trade-off calculation than the minimum total emission calculation because it has a higher selling price than DLF but produces higher emissions. At the trade-off, RBDPOL and RBDPS are produced in higher quantities as more RBDPO is passed on as raw materials, RBDPO is not exported. Part of RBDPOL is continued to produce double olein and PMF to meet global needs.

Torrefied pellet, PKE and CPKO are exported and the only derivative of RBDPKO that is exported is RBDPKS. CMC, bio-oil and almost all of the fatty acids are exported. CPO, fatty alcohol and biodiesel, sold only in quantities to meet only domestic needs.

The sales figures of each product resulted from multi-objective optimization is mentioned in Table 2.
Table 2. Product Sales Figures of Multi-Objective Optimization

| Product                  | Sales (ton) |
|--------------------------|-------------|
| CPO                      | 2,900,000   |
| POME                     | 2,030       |
| EFB                      | -           |
| PKS                      | -           |
| Palm Kernel              | -           |
| PFAD                     | -           |
| RBDPO                    | 2,610,000   |
| SCP                      | -           |
| Beta Carotene            | -           |
| Glycerin                 | 37,963      |
| Compost                  | 400,000     |
| Electricity              | 353,242     |
| DLF                      | 744         |
| Briquette                | 261         |
| Pellet                   | 322         |
| Torrefied Pellet         | 7,000,000   |
| Lignin                   | 5           |
| Cellulose                | 5,810,000   |
| Hemicellulose            | 1,053,495   |
| CPKO                     | 2,705,923   |
| PKE                      | 4,434,542   |
| PKS Charcoal             | 30          |
| Activated Carbon         | 1,900,000   |
| RBDPOL                   | 17,323,227  |
| RBDPS                    | 4,603,860   |
| FAME                     | 1,032,000   |
| Acrolein                 | 2,944       |
| Propylene Glycol         | 28,988      |
| RBDPKO                   | 730,800     |
| Caprylic Acid            | 715         |
| Capric Acid              | 738         |
| Lauric Acid              | 10,451      |
| Myristic Acid            | 3,514       |
| Palmitic Acid            | 1,820       |
| Stearic Acid             | 542         |
| Oleic Acid               | 3,318       |
| Bio-composite            | 8           |
| CMC                      | 897,958     |
| Glucose                  | 51          |
| Xylose                   | 131         |
| Bio-syngas               | 4,025,267   |
| Bio-oil                  | 90,474      |
| Double Olein             | 556,837     |
| PMF                      | 556,837     |
| Mid Stearin              | 3,219       |
| Fatty Alcohol            | 126,890     |
| MES                      | 3,740       |
| RBDPKOL                  | 168,360     |
| RBDPKS                   | 112,240     |
| HPKO                     | 1,149       |
Product | Sales (ton)
--- | ---
Bio-gas | 78
Bio-ethanol | 31
Xylitol | 0.02
Bio-methanol | 3
Bio-hydrogen | 3,272
Bio-gasoline

3.4. Sensitivity Analysis

Sensitivity analysis is done to assess recent issues related to Indonesian CPO exports to the EU due to the Renewable Energy Directive policy that would disrupt Indonesia's CPO exports to EU countries correspond to 3.2 million tons annually. In 2008, the EU has imposed anti-dumping tariff penalties on the export of biodiesel and Fatty Alcohol from Indonesia to the European Union. It also adds scenarios where biodiesel is also produced from CPO to see its effect on total selling price and total GHG emissions.

Table 3 shows the selling prices and emissions generated from various scenarios.

Table 3. Sensitivity Analysis Results

| Scenario | Total selling price (billion USD) | Emission (million-ton CO\textsubscript{2}e) |
|----------|----------------------------------|--------------------------------------|
| Eliminate all exports of CPO, fatty alcohol and biodiesel. | 51.68 | 88.05 |
| CPO as a source of biodiesel production and eliminated all exports of CPO, fatty alcohol and biodiesel. | 51.30 | 89.38 |
| Eliminates Indonesia's CPO exports to the EU by 3.2 million tons | 50.93 | 87.23 |
| Base case (Exports of CPO by 15.39 million tons) | 50.51 | 87.16 |

The three scenarios (base case, CPO export abolition to EU, and CPO-based biodiesel addition) are resulted in different values of total selling prices emissions from the trade-off. All of these scenarios resulted lower selling prices and only CPO-based biodiesel addition scenario which would have higher total GHG emissions compared to the trade-off. It can be seen that the decrease of selling price and emission of base case scenario and CPO export abolition to EU scenario are influenced by decreasing amount of CPO as the intermediate products for RBDPO, RBDPOL, RBDPS and biodiesel production. The emissions obtained from the CPO-based biodiesel addition scenario are higher than the trade-off due to its production pathway, one of which is directed to produce biodiesel and bio-oil. CPO based biodiesel produces higher emissions than those RBDPO, PFAD and their derivatives. Even though the emissions from production of RBDPO, PFAD and its derivatives is smaller than in the trade-off. This is coupled with higher bio-oil production which is one of the products with high emission factor.

4. Conclusions

Based on multi-objective optimization, selected production pathways are the production of 54 palm oil derivatives products to meet domestic needs and 21 of them can be exported comprised of 1 FFB derivative products (POME), 4 CPO derivatives products (RBDPOL, RBDPS, double olein and PMF), 1 POME derivative products (compost), 4 derivative products of EFB (cellulose, hemicellulose, activated carbon and CMC), 2 PKS derivative products (torrefied pellet and bio-oil), and 9 derived products of palm kernel (PKE, CPKO, caprylic acid, capric acid, lauric acid, myristic acid, palmitic acid, oleic acid and RBDPKS). The elimination of CPO exports, fatty alcohols and biodiesel does not
affect the selling prices and total emissions at the trade-off and higher total selling prices and emissions compared to base case.

Acknowledgments
This work has been carried out by the financial support of the Universitas Indonesia under the project "Hibah Publikasi Internasional Terindeks Untuk Tugas Akhir Mahasiswa" (PITTA) Fiscal Year 2018 number: 2557/UN2.R3.1/HKP.05.00/2018

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