Multi-Objective Optimization of Blending Strategy of FAME, HVO, and Petroleum Diesel

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Abstract. The utilization of biofuels based on palm oil could decrease greenhouse gasses (GHG) emitted by fossil fuels. The aim of this research is on the optimization of blending strategy of Fatty Acid Methyl Esters (FAME), Hydrogenated Vegetable Oil (HVO), Diesel CN48 (DCN48), and Diesel CN53 (DCN53) to meet the fuel quality standard, Euro2 and Euro4 by minimizing levelized cost of fuel supply and GHG emission. The process simulation is performed by Aspen Plus software, proceed by Life Cycle Analysis (LCA) calculation. The optimization is carried out by General Algebraic Modelling System (GAMS) with Cplex solver. The result showed the percentage of the optimal blending composition of fuel quality Euro2 were FAME 43.9 - 51.1%, HVO 2.6 - 40.1%, DCN48 15.3 - 17.6%, and DCN53 46.3 - 100% with LCOE was 0.55 - 0.864 USD/Liter and GHG intensity 599.46 - 3000.78 gCO2eq/Liter. For Euro4 specification consists of FAME 32.5%, HVO 28.6%, and DCN53 38.8% with LCOE were 0.637 - 0.786 USD/Liter and GHG intensity of 902.69 - 2863.03 gCO2eq/Liter.

1. Introduction
The demand for Indonesia's diesel in 2018 reached 30.36 million kiloliters (kL) along with the domestic production of petroleum diesel and biodiesel was 22.72 and 3.04 million kL, respectively [1]. Thus, increasing the import of diesel reached 4.61 million kL. The country has to face a rise in its current account deficit due to this import. To reduce petroleum fuel imports, starting from 2015, the Ministry of Energy and Mineral Resources issued Regulation No. 12/2015 regarding the mandate of mixing diesel fuel with FAME. In 2015, the government targets biodiesel blending for 20% later on, in 2020, the percentage of FAME will be increased to reach 30%. Using 30% of FAME, Indonesia's diesel imports are predicted to reduce by 3.82 million kL.

Biodiesel has potential to improve engine performance and reduce particulate exhaust emissions in compression-ignition (CI) engines. However, the blending fuel is required to meet the standard specifications set by the World Fuel Charter. Indonesia's emission target is an adaptation of the European emission target called the Euro in which the emission target in 2021 is Euro4.

Regarding the standard specification mentioned above, the blending diesel fuel no longer stems from petroleum diesel and FAME only, as paraffinic fuel such as HVO has the characteristic similar to petroleum diesel. Thus adding HVO into consideration has become an approach to fulfill the requirement of the standards. In the previous study, optimization is carried out by obtaining the least GHG intensity, as previously conducted by Abdulrazik [2], and obtaining the least LCOE with an optimal ternary blending HVO, FAME, and alcohol [3]. However, the two research which mentioned above does not focus on multi-objective optimization. The aim of this study is the optimization of biofuel
blending by minimizing production costs and GHG intensity. The result of the optimization could potentially be a guidance for the development of blended fuels in Indonesia.

2. Methods
This study is divided into five steps, first, build scenarios of the blending presented in Figure 1.

Figure 1. Blending fuels scenarios.

There are 8 scenarios in total in which each scenario consists of three fuels, the two of the fuels are biofuels (FAME and HVO) with different combination on the petroleum diesel cetane number (CN48 and CN53). Besides from the blending fuels, the standards of the blending fuels are based on the World Fuel Standard from Europe which called Euro and following Indonesia’s existing condition which follow Euro2 and the Indonesia’s goal toward Euro 4 specification. However, considering the petroleum diesel specification from Indonesia there are adjustments formed in order to achieve the Euro standard, which later be called Indo-Euro2 and Indo-Euro4.

The difference between the Indo-Euro2 and Indo-Euro4 scenarios is due to the condition of Indonesian refineries which are unable yet to produce diesel fuel with sulphur content less than 10 ppm compare to refineries in Europe which able to produce Ultra Low Sulphur Diesel (ULSD). Therefore, additional scenario is needed as an adaptation of Indonesia with the provisions of the Euro2 and Euro4 specifications standard. The scenarios can be seen in Table 1.

Table 1. Blending scenarios.

| Scenarios | Standard       | Blending Fuels          |
|-----------|----------------|-------------------------|
| Scenario 1 (S1) | EURO-2          | FAME - HVO - DCN 48     |
| Scenario 2 (S2) |                 | FAME - HVO - DCN 53     |
| Scenario 3 (S3) | INDO-EURO2      | FAME - HVO - DCN 48     |
| Scenario 4 (S4) |                 | FAME - HVO - DCN 53     |
| Scenario 5 (S5) | EURO-4          | FAME - HVO - DCN 48     |
| Scenario 6 (S6) |                 | FAME - HVO - DCN 53     |
| Scenario 7 (S7) | INDO-EURO4      | FAME - HVO - DCN 48     |
| Scenario 8 (S8) |                 | FAME - HVO - DCN 53     |

After completing the scenarios design, the first step is to simulate the process production of FAME and HVO to attain the diesel product properties, technical performance, sizing, along with the cost production through process simulation using Aspen Plus V11. However, for certain specifications cite, viscosity, sulphur content, lubricity are extracted from [4] and [5].

Second, LCA analysis calculated with system boundary of Well-to-Wheel (WTW). The LCA starts with cultivation of palm oil until the extraction, FAME and HVO distribution and storage are extracted.
from GREET based calculation [6], the inventory process taken from the simulation data, and the petroleum diesel data along with the combustion earned from Toyota Motor Corporation [7].

Result of the process simulation and calculation of the GHG intensity are being optimized using General Algebraic Modelling System (GAMS) to earn the minimum LCOE and minimum GHG intensity. Therefore, two different values are obtained for each objective function. From the two values, one objective function is determined to be the limit because the multi-objective optimization method chosen is a \( \varepsilon \)-Constraint Method. The objective function being constrained is the GHG intensity. Afterwards, the points of minimum and maximum emission can be determined and then, pareto curves can be formed. From the Pareto curve, then the compromised solution can be determined using the Multi-Criteria Decision Making (MCDM) with the TOPSIS method.

2.1. Process Simulation
A process flowsheet is designed using Aspen Plus V11 with base capacity of HVO production is set to 1 million tons per year similar to the commercial HVO production and the base capacity of FAME production is 300,000 tons per year.

2.1.1. FAME. The manufacture of FAME in this simulation uses Refined Bleached Degummed Palm Oil (RBDPO) as raw material, which is a derivative product of CPO that has gone through a previous refining process. With production capacity mentioned above, the required CPO in the process is 7031.02 kg of CPO/hour. The process of making FAME itself consists of several steps, namely the transesterification reaction, methanol recovery, water washing, FAME purification, and alkaline removal.

2.1.2. Glycerol Steam Reforming (GSR) – HVO. GSR is being processed to produce hydrogen which will later on be utilized in the HVO manufacturing process. With the HVO production capacity mentioned above, 47,704 kg of hydrogen/hour is needed. The process of GSR described further in the research of steam reforming glycerol [8]. In this simulation, the HVO plant not only produces HVO but also bio-jet fuel and naphtha with HVO specifications referring to the EN 15940: 2016 standard. The process of HVO production described further in the preliminary design of the HVO production [9]. The hydroisomerization reactor uses a yield reactor based on experimental data [10]. Separation was carried out for hydrogen recovery from both reactors. Then, the C3 and C4 hydrocarbons are separated to be burned so that the steam can be reused for production. The resulting product is also purified using distillation to separate green naphtha, HVO, and bio-jet fuel.

2.2. Life Cycle Analysis
Well-to-Wheel (WTW) is more applicable to crude oil resources and their derivatives. WTT includes the process of producing raw materials up to the car’s fuel tank. Tank-to-Wheel (TTW) includes the process of burning fuel in the engine so that WTW is a total of WTT and TTW. However, for the vegetable oil such as FAME and HVO the calculation starting from cultivation, fuel production process, until the distribution of the fuels which assumed as WTT.

2.3. Multi-Objective Optimization
After LCOE is obtained, the optimization could be proceeded to get the minimum LCOE and minimum GHG intensity with GAMS (Cplex solver) which can be plot into pareto curves so that the results of the compromised solution can be obtained. The objective function equations are stated the following equations:

\[
\text{Objective function 1 } \equiv \text{OF}_1 = \sum x_i C_i \tag{1}
\]

\[
\text{Objective function 2 } \equiv \text{OF}_2 = \sum x_i F_E_i \tag{2}
\]
The $x_i$ is the volume fraction of the fuel, $C_i$ is the production cost of the diesel (USD/Liter), $F_i$ is the GHG intensity to produce the diesel (gCO$_2$eq/Liter). In this study, there are constraints on the fuel property specifications as follows:

$$CN_{\text{min}} \leq CN_{\text{blend}}$$

$$\rho_{\text{min}} \leq \rho_{\text{blend}} \leq \rho_{\text{max}}$$

$$\mu_{\text{min}} \leq \mu_{\text{blend}} \leq \mu_{\text{max}}$$

$$SC_{\text{blend}} \leq SC_{\text{max}}$$

$$WC_{\text{blend}} \leq WC_{\text{max}}$$

$$L_{\text{blend}} \leq L_{\text{max}}$$

CN is cetane number, $\rho$ is density (kg/m$^3$), $\mu$ is viscosity (mm$^2$/s), SC is sulphur content (ppm), WC is water content (mg/kg), and L stands for lubricity (micron). The minimum and maximum value mentioned above use the standardized upper and lower limit shown in Table 2.

**Table 2. Specification properties Euro-2 and Euro-4.**

| Properties       | EURO-2 | EURO-4 |
|------------------|--------|--------|
|                  | Lower Limit | Upper Limit | Lower Limit | Upper Limit |
| Cetane number    | 51     | -      | 53          | -          |
| Density (kg/m$^3$) | 815    | 850    | 815         | 840        |
| Viscosity (mm$^2$/s) | 2      | 4      | 2           | 4          |
| Sulphur content (ppm) | -      | 500    | -           | 50         |
| Lubricity (micron) | -      | 460    | -           | 460        |
| Water content (mg/kg) | -      | 200    | -           | 200        |

There are mixing rules to blend the diesel, specifically for each property such as density, viscosity, sulphur content, lubricity, and water content [12] and [13]. For $x_i$ is the volume fraction and $y_i$ is the mass fraction. However as stated earlier in this study, the condition of refineries in Indonesia has not yet fully comply with the standard therefore, Indonesia has its own standard which refer to the worldwide fuel charter.

**Table 3. Indo-Euro2 and Indo-Euro4.**

| Properties       | INDO-EURO2 | INDO-EURO4 |
|------------------|------------|------------|
|                  | Lower limit | Upper limit | Lower limit | Upper limit |
| Cetane number    | 48         | -          | 51          | -          |
| Density (kg/m$^3$) | 815       | 860        | 815         | 860        |
| Viscosity (mm$^2$/s) | 2         | 4.5        | 2           | 4.5        |
| Sulphur content (ppm) | -         | 2500       | -           | 300        |
| Lubricity (micron) | -         | 460        | -           | 460        |
| Water content (mg/kg) | -         | 500        | -           | 500        |
3. Result and discussion

3.1. Overall system efficiency
The system efficiency for the simulated fuels is shown in Table 4.

Table 4. Process simulation result.

| Parameter       | Units | FAME [14] | HVO [9] |
|-----------------|-------|-----------|---------|
| Product/Feed    |       |           | 3       |
| Ratio           |       | 1.74      |         |
| Yield           | %     | 91.65     | 90-95   |
| Conversion      |       | 52        | 93      |
| Energy          | %     | 53.11     | -       |
| Efficiency      |       | 76        | 79      |
| Purity          | %w/w  | 99.82     | 99.7    |
|                 |       | 52.17     | 77.23   |

Properties

| Parameter       | Unit  | FAME  | HVO  |
|-----------------|-------|-------|------|
| Cetane          |       | 66.66 | 63   |
| Number          |       | 78.49 | 99.00|
| Density         | kg/m³ | 877.64| 874  |
| Viscosity       | mm²/s | 4.5   | 4.372|
| [4]             |       | 3     | 3.704|
| Sulphur Content | ppm   | 0     | 1    |
| [5]             |       | 1     | 9    |
| Lubricity       | micron| 186   | 203  |
| [5]             |       | 650   | 607  |
| Water content   | mg/kg | 270.87| 62   |
|                 |       | 42    | 39   |

Based on the simulation result, the mass purity of FAME reached 99.82% and has been validated with the standard product of ASTM 6751 with the minimum mass purity of 99.65%. The deviation data for the ration of FAME to CPO is 4.71% as the result of the greater the feed compare to the study [5]. For HVO simulation result, the yield conversion is different because the product in the study [4] are not producing bio-jet fuel as in this study the products are HVO, bio-jet fuel, and naphtha. Another reason is the hydrogenation reaction used in this study is using equilibrium equation therefore ratio of product/feed greater which then affected the greater yield production efficiency.

Table 5. GSR plant simulation technical performance evaluation.

| Parameter       | Unit   | Simulation |
|-----------------|--------|------------|
| Glycerol        | %      | 100.00     |
| conversion      |        |            |
| H₂/Glycerol     | -      | 4.01       |
| Mole Ratio      |        |            |
| H₂ Yield        | %      | 30.86      |
| Selectivity     | %      | 100.00     |
| Energy Efficiency| %    | 50.42      |
| PSA Recovery    | %      | 71.30      |
| Glycerol/Hydrogen| w / w| 8.13       |
| Ratio           |        |            |

Yield of the hydrogen has increased for 0.3%. Actually, the conversion results from Water Gas Shift (WGS) reactor is large, which is equal to 40.52% but after entering the Pressure Swing Adsorption (PSA) the final results obtained reduced because of the impurities with H₂ 2%, H₂O 16%, CO 28%, and
CO₂ 52% as the result of impurities. Those impurities are being recirculated again in natural gas burning, the CO₂ content that is recirculated in the combustion of natural gas is equal to 6% and still follow into the limit of CO₂ content for burning natural gas, which is 12% [15].

3.2. Cost Evaluation
Costs are calculated by using Aspen Process Economic Analyzer. Additional costs for the catalyst and the reactor are estimated separately the added to the capital cost result of Aspen. LCOE of FAME is 0.69 USD/Liter however, this calculation is not a final calculation because there is a joint cost effect between productions FAME with glycerol as a by-product. The percentage for FAME is 95% and glycerol is 5%. Therefore, the LCOE of FAME is 0.66 USD/Liter and LCOE of glycerol is 0.03USD/Liter.

The LCOE GSR is 4.69 USD/kg hydrogen not much different from reference data [16] which stated 4.86 USD/kg of hydrogen for the base case scenario. When compared with the LCOE Steam Methane Reforming (SMR) which was 1.27 USD/kg hydrogen, LCOE GSR is much more expensive than LCOE of SMR. This is due to the small hydrogen conversion of 4 moles hydrogen per 1 mole of glycerol so that there is little hydrogen produced but the need for raw materials is large.

The LCOE for HVO is 2.44USD/Liter which shows the total product produced in the simulation, namely HVO, naphtha and bio-jet fuel therefore by using weighted joint cost, the HVO percentage is 51.33% so that the LCOE earned for HVO is 1.25 USD/Liter. The cost breakdown can be generated for FAME and HVO, in which has been integrated with the LCOE GSR in Figure 2.

![Figure 2. LCOE of FAME and GSR-HVO.](image)

It can be seen in Figure 2 above, that the percentage of (CPO) as FAME raw material taken up to 94.8% while according to APEC (2013) the percentage of raw material costs is 83%. This difference is due to the conversion generated by the process simulation 4.71% greater. Thus, for FAME, the LCOE is heavily influenced by the feedstock cost.

For HVO production itself, there is no literature using GSR so the cost breakdown cannot be validated. However, it can be seen from Figure 2 that the cost of producing hydrogen is very large, which is 58%, this is because the cost of producing 1 kg of hydrogen costs 4.69 USD whereas when compared to hydrogen production using other technologies, the cost of producing hydrogen through GSR technology is more expensive.

The fundamental technological difference between FAME and HVO production is one of the factors that causes the production cost between FAME and HVO to differ up to 0.59USD/Liter. The hydrogenation process, which requires more expensive costs by using two reactors, namely hydrogenation and hydroisomerization, are certainly bigger when compared to the production of FAME which only uses a transesterification reactor.
3.3. GHG Intensity

The GHG intensity of CO$_2$ of the fuels produced and burned are presented in the Figure 2.

![Figure 3. LCA FAME, HVO, and Petroleum diesel (Well-to-Wheel).](image)

The GHG intensity of GSR is 78.19 gCO$_2$eq/MJ. The difference in the reference study [17] with amount of 105.42 gCO$_2$eq /MJ is because of the allocation factor with FAME is 0.96 and glycerol is 0.04. In addition, the operating conditions in the study use a large pressure of 25 bar and a temperature of 800°C while the GSR simulation in this study uses a temperature of 4 bar and a temperature of 575°C because of these differences, the resulting emissions are different. When compared with the SMR emission factor of 10.99 kgCO$_2$eq/kg hydrogen. Not much different from SMR, although GSR from biomass. Steam reforming using glycerol produces 3 moles of CO$_2$ stoichiometry. This CO$_2$ release makes the GHG value even greater.

As in the Figure 3, the WTT of the petroleum diesel also presented and through this figure, it can be concluded that the production of petroleum diesel is producing lower emission compare to FAME and HVO. However, the diesel emission factor is much greater during the internal combustion process with the amount of 74.75 gCO$_2$eq/MJ. Thus, the result of the GHG intensity is 89.3-90.28 gCO$_2$eq/MJ petroleum diesel and HVO has a GHG value of 50 gCO$_2$eq/MJ HVO.

The composition of HVO with diesel is different so that the diesel engine, which is why HVO cannot yet fully utilize the properties of HVO. Adjustment of the machine parameters need to be made. One of them is the cetane number so that it can compensate the fuel ignition when the engine is started. The fuel consumption using HVO will be around 2-8% more than diesel because it has a lower HVO density of 6% due to the natural properties of paraffinic fuels. Previously it was stated that with a lower density diesel consumption would increase, but with a higher HHV HVO value, HVO consumption would remain lower than diesel.

For the Tank-to-Wheel of HVO, there is not enough data on the use of HVO in light-duty vehicles (vehicles with feeds weighing less than 3 tons), so far the HVO has only been tested under steady operating conditions, while most light-duty vehicles operate in a transient state. The emission reduction by HVO actually occurs the most in the Particulate Matter (PM), CO, and unburned hydrocarbon. CO$_2$ reduction is only about 6% with CO$_2$ emissions of 1146g with diesel emissions of 1194g, this lower emission is due to the carbon content of HVO as much as 84% while the carbon content of diesel is 86.2%.

3.4. Optimization of the blends
Initially the date of WTW with two solutions on each scenario are being plot into the pareto curve to get the compromised solution presented in Table 6.

Table 6. Compromised solution of WTW.

| Scenario | Compromised Solution |
|----------|----------------------|
|          | Emissions (gCO2eq / Liter) | LCOE (USD / Liter) | FAME (%) | HVO (%) | Solar (%) |
| 1 (DCN48) | 2443.94 | 0.864 | 44.7 | 40.1 | 15.3 |
| 2 (DCN53) | 3000.78 | 0.624 | 51.1 | 2.6 | 46.3 |
| 3 (DCN48) | 3045.09 | 0.552 | 48.6 | 0 | 51.4 |
| 4 (DCN53) | 2863.03 | 0.637 | 68.8 | 1.6 | 29.6 |
| 6 (DCN53) | 2739.12 | 0.786 | 32.5 | 28.6 | 38.8 |
| 7 (DCN48) | 2521.48 | 0.784 | 64.4 | 24.9 | 10.8 |
| 8 (DCN53) | 2863.03 | 0.637 | 68.8 | 1.6 | 29.6 |

In a compromised solution, when MCDM is carried out with the ideal point at point $(x, y)$ with $(x_{\text{min}} \text{OF}_2, y_{\text{axis}} \text{OF}_1)$ for scenarios 1, 6, and 7, they have the same characteristics as the optimal point chosen (low LCOE but high GHG intensity). This is because the difference between maximum and minimum emissions is not much different, namely 15.86-23.14 compared to other scenarios with an average difference of 47.94. Since the GHG intensity value for each point is not much different, the optimal point is chosen with the trend of the minimum LCOE.

Scenarios 2, 4, and 8 have the same characteristics in choosing a compromised solution, when the minimum HVO percentage is blended. Compared to emissions, the optimal points taken from scenarios 2, 4, and 8 are looking for the lowest LCOE possible but still considering the GHG intensity produced.

Scenario 3 chooses the optimal point right when the HVO component has not been added to the blending diesel. This shows that the optimal point is chosen to consider LCOE because after the HVO component is added to the mixed fuel, the LCOE value will increase. When the HVO component has not being blended, the difference between each LCOE value is 0.17 but when the HVO is blended, the difference in LCOE value increases to 0.23 and will continue to increase as the HVO component increases.
In the portfolio blending in Figure 4 above, scenario 3 only contains two mixed fuels, FAME and diesel, so this scenario has a lower selling price compared to other scenarios that contain HVO. Scenarios 2, 4 and 8 have three fuel components, but the HVO component is blended in small amount compared to other fuel components so that the selling price of the 2,4,8 scenario is lower than the scenario 1,6, and 7 which has a greater percentage of HVO.

4. Conclusion
Blending portfolio for Euro2 diesel specifications contains FAME 43.9-51.1%, HVO 2.6-40.1%, DCN48 15.3-17.6%, and DCN53 46.3-100% along with the LCOE of the blending is 0.55-0.864 USD/Liter and the GHG intensity reached 599.46-3000.78 gCO₂eq/Liter. Then, blending portfolio for Euro4 diesel specifications contains FAME 32.5%, HVO 28.6%, and DCN53 38.8% along with the LCOE of the blending is 0.637-0.786 USD/Liter and the GHG intensity reached 902.69-2863.03 gCO₂eq/Liter. Further research should be conducted for the HVO combustion in diesel engines, especially in light duty vehicles, specifically in transient operating conditions.

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