Techno-economic assessment for optimal electricity and diesel fuel production using corncob gasification–Fischer Tropsch process

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Abstract. Biomass gasification technology has been developed in Indonesia in the last 30 years. However, the use of synthetic gas directly on diesel engine and steam turbine for electricity generation has a relatively low efficiency. New technology has been emerged to integrate thermal gasification with Fischer-Tropsch (FT) synthesis which then can be combined with heat and electricity production. This paper consists of techno-economic study for optimal electricity and diesel fuel production using corncob gasification integrated with FT process. Optimal production (409 GWh electricity, 58,900 kL fuel) can be achieved when using air and operating pressure 25 bar. Calculated production cost is 6,569 IDR/kL FT fuel and 245 IDR/kWh electricity. With average Indonesian electricity tariff 1,123 IDR/kWh, BGFT electricity production cost is much lower, about 22% of Indonesian electricity tariff. Corncob price change has higher effect on electricity production cost than water price change. So, if the electricity cost wants to be hold in economic level, then the corncob price should be held constant. The price will stay constant if there are no competitor that would use corncob as raw material. As of now, corncob still considered as waste that are not used for economic activities.

1. Introduction
Electricity production cost in Indonesia are as high as 911 to 2,677 IDR/kWh [1]. Those high production cost causes the high price of Indonesian electricity. One of cheaper way to produce electricity is through gasification process. Gasification process has been developed in Indonesia since the last 30 years, especially in decentralized power plant for remote area. The use of gasifier gas product, called synthetic gas or sync-gas, directly for electricity generation using diesel engine and steam turbine has a relatively low efficiency [2]. Based on review in Asadullah, the most challenging barriers in electricity generation from biomass is the gasification of biomass and gas cleaning part because there are a really strict specification of gas composition and tar concentration when using gas for electricity generation [3].

New technology has been emerged to produce diesel fuel from biomass via thermal gasification followed by Fischer-Tropsch (FT) synthesis which can be combined with heat and electricity production [4,5]. That technology is believed to give better thermal efficiency. Based on Tijmensen et al., maximum overall efficiency is 51%, 40% of it is in the form of FT liquids [4]. Techno-economic of biomass integrated Gasification-Fischer Tropsch (BGFT) processes in general is learned in [6–9]. The same study
can be done in Indonesia because it is an agriculture country which has many biomass resources with high energy content such as palm oil empty fruit bunch (17.75 MJ/kg), corncob (16.97 MJ/kg), and rice husk (14.91 MJ/kg) (calculated from Liu et al. [10] and Laohalidanond et al. [11]. Based on its water content, corncob has less moisture than palm oil empty fruit bunch and rice husk. Corncob is available in a lot of Indonesian Province, the highest reserves are in East Java, Central Java, Lampung, South Sulawesi, and East Nusa Tenggara. Because of its high reserves and less utilization, corncob can be considered for BGFT feed.

This paper purposed to study the opportunity for corncob utilization into electricity through gasification process and combine cycle technology. Combination of biomass gasification with FT process, also known as BGFT, can be used to produce diesel fuel and heat. Heat product can be used to generate electricity. Optimum BGFT operation in electricity generation is conducted with techno-economic approach. The production cost is then compared with conventional electricity production cost in Indonesia.

2. Approach and method

2.1. Problem formulation

Approach that used in this study can be seen in figure 1. We can see that the conventional gasification process will produce syn-gas which then will be processed into FT fuel. Heat produced can then be used to produce electricity using Heat Recovery Steam Generation (HRSG).

![Figure 1. Process approach for dual energy production.](image)

2.2. Method

Heat capacity of biomass can be calculated using correlation in Liu et al. [10] based on its proximate and elemental analysis result. Analysis for corncob has been done in Laohalidanond et al. [11]. Those heating value can be converted into energy through gasification process. Biomass gasification consists of several reaction which convert solid fuel into combustible gas as figured out by equation (1). Oxygen, air, steam, or combination between those compounds may act as gasification agent [9].

\[
\begin{align*}
\text{Drying process (100-250°C)} & \quad \text{wet biomass} \rightarrow \text{dry biomass} + \text{H}_2\text{O} \\
\text{Pyrolysis (250-500°C)} & \quad \text{dry biomass} \rightarrow \text{C} + \text{H}_2\text{O} + \text{tar} + \text{CH}_4 \\
\text{Oxidation (1200°C)} & \quad \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \\
\text{Reduction (800-1000°C)} & \quad \text{C} + \text{CO}_2 \rightarrow 2 \text{CO} \\
& \quad \text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2
\end{align*}
\]

Gasification product generally consist of carbon monoxide (CO), carbon dioxide (CO\(_2\)), hydrogen (H\(_2\)), and a little low chain hydrocarbon (ethene, ethane), water, nitrogen, and several contaminants such as char particle, ash, tar, high chain hydrocarbon, alkali, ammonia, acid, etc. [12]. Reduction reaction is controlled between 800 to 1200°C to optimize CO formation. After gasification process, gas product need to be cleaned and treated before being used for FT reaction [12]. BGFT process is consist of 4 main systems: biomass gasification, cleaning and conditioning of synthetic gas, Fischer-Tropsch synthesis, and fuel upgrading and electricity production. Overall BGFT process is shown in figure 2.
Products of FT reaction are lies between light hydrocarbon (C$_1$ and C$_2$), LPG (C$_3$ and C$_4$), naphtha (C$_5$ – C$_{12}$), diesel (C$_{13}$ – C$_{19}$), and wax (C$_{20+}$). Main reaction in FT synthesis is shown in equation (3). -CH$_2$- is basic component for long chain hydrocarbon. The main characteristic that influence FT synthesis performance is selectivity. FT process selectivity is determined by chain growth probability, which state the probability of -CH$_2$- chained with other -CH$_2$- group. Product of FT reaction is hydrocarbon chain with different length. Selectivity of C5+ product (SC$_{5+}$) is favorable to get maximum number of long chain hydrocarbon. The number of C$_1$-C$_4$ hydrocarbon in flue gas of FT reactor can be used for electricity generation. Long chain hydrocarbon forming reaction is endothermic reaction which need high energy as shown in equation (3). Based on energy needed for reaction in equation (1) and (2), BGFT temperature need to be controlled to give maximum number of long chain hydrocarbon product. Correlation between hydrocarbon yield with chain growth probability [10] is illustrated with carbon chain distribution equation (3).

\[
\text{CO + 2 H}_2 \rightarrow -\text{CH}_2- + \text{H}_2\text{O} \quad \Delta H_{\text{FT}} = -165 \text{ kJ/mol} \tag{2}
\]

\[
w_{n} = n \alpha^{n-1} (1-\alpha)^{2} \tag{3}
\]

with $\alpha$ is probability of chain growth, depends on catalyst type; $n$ is number of atom C in hydrocarbon chain; and $w_{n}$ is hydrocarbon mass fraction that has $n$ number of C atom

Equation (3) shows mass fraction of hydrocarbon chain which represented by $w_{n}$ while (1-$\alpha$) represent the probability of -CH$_2$- chain termination. When we use Fe based catalyst, the value of $\alpha$ is 0.67 to 0.71 while for Co based catalyst, $\alpha$ value is 0.76 to 0.83. Higher operating pressure in FT reactor with Co catalyst will produce longer chain hydrocarbon. Chain growth probability for each kind of hydrocarbon are shown in table 1. Implementation of Co based catalyst may produce optimum hydrocarbon mass fraction and better chain growth probability.

| Fuel   | Hydrocarbon Mass Fraction for Fe based catalyst | Hydrocarbon Mass Fraction for Co based catalyst |
|--------|-----------------------------------------------|-----------------------------------------------|
| LPG    | 0.38 – 0.50                                   | 0.18 – 0.30                                   |
| Gasoline | 0.30 – 0.38                                  | 0.30 – 0.38                                  |
| Diesel | 0.05 – 0.18                                   | 0.25 – 0.38                                  |
Water-gas shift (WGS) reaction will happen when FT synthesis is done using Fe catalyst. When gasification product has low $\text{H}_2/\text{CO}$ (lower than 2) then WGS reaction is needed to increase the ratio. Higher partial pressure of $\text{H}_2$ and $\text{CO}$ will give higher selectivity of diesel product. Inert ($\text{CO}_2$, $\text{CH}_4$, $\text{N}_2$, Ar, and light hydrocarbon) will not disturb reaction but they will decrease $\text{H}_2$ and $\text{CO}$ partial pressure and indirectly influence FT product conversion and selectivity [10].

Simulation of BGFT process for fuel and electricity production from corncob has been done in literature [13]. BGFT process is simulated in several variation to get highest fuel and electricity product. Each variation has differences in operating pressure and gasification agent. The difference in gasification pressure and agents will give different syn-gas composition, which then will influence fuel and electricity output from BGFT process. Electricity production cost is then calculated using spreadsheet.

3. Results and discussion
Simulation will be conducted to get better result of electricity production through Biomass Gasification – Fischer Tropsch (BGFT) process. Electricity in Indonesia is conventionally produced using energy from several raw materials to rotate the turbine. Mechanical energy from turbine rotation will be converted into electricity. Utilization of different raw materials will result in different electricity production cost. Those conventional electricity production cost will be compared with the cost from BGFT process. Electricity production cost using conventional technology in Indonesia can be seen in table 2.

Table 2. Electricity production cost and tariff in Indonesia [14].

|                | 2014   | 2015    | 2016    | 2017    | 2018    |
|----------------|--------|---------|---------|---------|---------|
| Average Tariff (IDR/kWh) | 939.7  | 1,034.5 | 991.4   | 1,105.1 | 1,123.0 |
| Average Production Cost (IDR/kWh) | 1,296.7| 920.2   | 856.3   | 1,087.5 | 1,160.9 |

3.1. Result
The different in operating pressure and agents used in gasification process gives different syn-gas composition. Simulation result for corncob gasification in several temperatures are shown in table 3. BGFT Process is then simulated using that syn-gas composition to get the number of fuel and electricity produced.

Table 3. Simulation result.

|                | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| **P (bar)**   | 1.3     | 1.3     | 1.3     | 6       | 6       | 6       | 25      | 25      | 25      |
| **T (°C)**    | 850     | 850     | 850     | 850     | 850     | 850     | 850     | 850     | 850     |
| **O** _2_     | 21%     | 95%     | 80%     | 21%     | 95%     | 80%     | 21%     | 95%     | 80%     |
| **N** _2_     | 79%     | 5%      | 20%     | 79%     | 5%      | 20%     | 79%     | 5%      | 20%     |
| **H** _2_     | 13.7%   | 24.5%   | 23.9%   | 12.7%   | 23.8%   | 23.2%   | 12.7%   | 24.0%   | 23.4%   |
| **CO**        | 11.5%   | 19.8%   | 19.4%   | 11.0%   | 20.0%   | 19.5%   | 11.1%   | 19.5%   | 19.0%   |
| FT Fuel Produced (kL/year) | 57,987 | 55,691 | 55,834 | 58,939 | 56,249 | 56,291 | 58,900 | 55,843 | 55,945 |
| Electricity produced (GWh) | 330    | 203     | 212     | 305     | 207     | 214     | 409     | 258     | 268     |
| FT fuel production cost (IDR/L) | 6,804  | 6,532   | 6,651   | 6,603   | 6,331   | 6,464   | 6,569   | 6,308   | 6,443   |
| Electricity production cost (IDR/kWh) | 311    | 466     | 454     | 331     | 446     | 441     | 245     | 353     | 348     |

The highest electricity production, 409 GWh per year, is produced using gasification operating pressure 25 bar and air as gasification media. Using that variation, 58,900 kilo Litres diesel fuel are also produced per year. Corncob raw materials needed for the production is 300,000 ton/year. The cost needed to
produce electricity and diesel fuel from corncob are consistent if investment cost 4.3 trillion IDR, working capital for first year 52.9 billion IDR, corncob price 700 IDR/kg, and water cost 5,000 IDR/m$^3$. Using that cost and product price, production cost of electricity and FT can be calculated. Using those element cost, calculated production cost for FT fuel is 6,569 IDR/litre and production cost for electricity is 245 IDR/kWh.

### 3.2. Discussion

Higher gasification pressure gives higher fuel and electricity produced. It happened because higher pressure will have effect on higher CO and H$_2$ partial pressure and better selectivity for long chain hydrocarbon produced. Sensitivity analysis of raw materials price change effect on production cost is shown in figure 3. It is shown that corncob price change has higher effect on electricity production cost than water price change. So, if the electricity cost wants to be hold in economic level, then the corncob price should be held constant. The price will stay constant if there are no competitor that would use corncob as raw material. As of now, corncob still considered as waste that are not used for economic activities.

![Figure 3. Sensitivity of electricity cost based on water and corncob price change.](image)

The comparison between electricity cost from BGFT process with other conventional process is shown in figure 4. We can see from figure 4 that conventional electricity production cost is spread between 352.4 to 7,672.7 IDR/kWh, while average Indonesian electricity tariff in 2018 is 1,123 IDR/kWh. BGFT electricity production cost is much lower, as low as hydroelectric power plant production cost. The cost is about 22% of Indonesian electricity tariff.

![Figure 4. Comparison of electricity production cost from several electricity generation technology in Indonesia (processed from Tijmensen et al. [4]).](image)
4. Conclusion
Optimal electricity and diesel fuel production using corncob BGFT process can be achieved when using air as gasification agent and operating pressure 25 bar. With that operating condition, 409 GWh electricity and 58,900 kilo litre fuel can be produced per year. Calculated production cost for FT fuel is 6,569 IDR/kilo litre and production cost for electricity is 245 IDR/kWh. Conventional electricity production cost is spread between 352.4 to 7,672.7 IDR/kWh, while average Indonesian electricity tariff in 2018 is 1,123 IDR/kWh. BGFT electricity production cost is much lower, about 22% of Indonesian electricity tariff. Corncob price change has higher effect on electricity production cost than water price change. So, if the electricity cost wants to be hold in economic level, then the corncob price should be held constant. The price will stay constant if there are no competitor that would use corncob as raw material. As of now, corncob still considered as waste that are not used for economic activities.

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