Economic and Life Cycle Assessments of Integrating Gasification Unit into Production Unit of Pellet from Fallen Leaves and Twig

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Abstract. Conversion of fallen leaves and twigs from urban waste into pellets may be one of several options to reduce the amount of waste transported to the landfill. However, the production of pellet needs very high mechanical energy or electricity. A case study has been conducted to evaluate the advantages and disadvantages of integrating a gasification technique into the production unit. In this integrated unit, the source of electricity for the pellet production was based on the conversion of a portion of pellet product to gaseous fuel which was then used as substitute of diesel fuel for running an electricity generator set. Three scenarios for supplying the electricity were compared: (i) scenario-A: from PLN (national grid, coal fired power plant), (ii) scenario-B: diesel-generator set; and (iii) scenario-C: diesel-genset and gasification unit. Total CO₂ emissions in the production of pellet were as follows (kg CO₂ eq/ton pellet): 81.8, 47.2 and 16.3 for scenario-A, B and C respectively. Due to the addition cost of investment, the integrated pellet production and gasification unit needed a Payback Period of about 5.6 years, while those of diesel based electricity and PLN were 5.1 and 4.8 years respectively. Data for this study was obtained from experiments on a pellet production unit with a design capacity of about 9 ton/week. The diesel engine was run in dual fuel mode using producer gas from the gasification of pellet. The producer gas heating values were in the range of 3300-4600 kJ/Nm³. Oil saving in dual fuel operation was up to 70%.

1. Introduction
Municipal solid waste (MSW) is a problem in many big cities in Indonesia, including Depok with population of 2.3 million and generation of 1300 ton/day MSW [1]. With this high waste generation, the disposal landfill for City of Depok in Cipayung is already over capacity in this year 2020. A program for sorting waste into several types have been applied at several temporary collection unit (TPS, tempat penampungan sementara). A part of sorted waste is woody or other hard biomass that may be utilized as a raw material for pellets.

Biomass pellets become an attractive commodity and grow to international market [2]. Wood pellets may be used as solid fuel for cooking in households and small-medium enterprises. Wood pellets, MSW pellets and also RDF (refuse derived fuel) are also adaptable to cofiring with coal as an option toward a carbon-free energy intensive industries [3].
Gasification is one of three main thermochemical conversions of biomass to gaseous fuel [4, 5, 6]. Producer gas (gaseous fuel from gasification using air as a gasifying medium) contains H₂, CO, CO₂, and CH₄. Having a heat combustion of about 4000 kJ/Nm³, this producer gas can be used as a substitute for liquid fuel in an internal combustion engine [7].

Integrating gasification technology in wood pellet production plant may save electricity bill, and in addition CO₂ emission may also be reduced. In this concept, the gasification system is fueled with a portion of pellets product. Evaluation of operating cost and CO₂ emission in the integrated gasification and pellets production plant are presented in this paper. Comparisons were made for three schemes in supplying electricity (see Figure 1).

2. Methodology
Experiments were carried out in the existing pellet production plant in City of Depok. This pellet production plant consists of a pellet production line and a diesel engine-generator set (Figure 1). Power for this plant is supplied from electricity grid (PLN) with a capacity of about 40 kW. This study dealt with the following aspects:

a. experiments on gasification of pellets to evaluate the performance of the gasification unit
b. operation of the diesel engine with dual fuel (mixture of petroleum fuel and producer gas)
c. testing the real capacity of pellets machineries
d. simple economic evaluation to see the feasibility of self-supplying electricity in a pellets production plant
e. study on the potential reduction of CO₂ emission.

3. Results and Discussion

3.1. Gasification and Diesel-Generator
The gasifier was an open core down draft type with a design capacity of 20 kg/h fuel with palm kernel shell. The producer gas (product of air-gasification) was firstly cooled and then filtered for tar removal. A typical analysis of wood pellets used in this study are presented in Table 1. The proximate and ultimate analysis of wood pellet used in this research was comparable to those reported in [8]. As expected, the gasification unit could be operated smoothly for 6 hours at a capacity up to 20 kg/h. However, the pellet mass conversion in the gasification process was only 73%, as indicated by the difference of ash content in original pellets to that in the char residue after gasification.

The producer gas composition and heating value were satisfactory (Table 2). This producer gas could be fed into the diesel engine for dual fuel operation. At a power output of about 22 kW, the oil saving in the dual fuel operation was up to 70%, meaning that 70% energy intake of the engine came from the producer gas. Of course, the oil saving depended on the producer gas composition and on the adjustment of gas to air ratio by the operator.
Table 1. Proximate and ultimate analysis of wood pellet.

| No. | Characteristics          | wood pellet, [8] | this work | char residue after gasification |
|-----|--------------------------|-----------------|-----------|--------------------------------|
|     | Proximate Analysis (wet basis) |                 |           |                                |
| 1   | Moisture Content         | 12.00%          | 12.10%    | 3.63%                          |
| 2   | Ash                      | 1.00%           | 4.36%     | 14.20%                         |
| 3   | Volatile matter          | 79.19%          | 67.68%    | 17.60%                         |
| 4   | Fixed Carbon             | 7.83%           | 15.86%    | 64.57%                         |
|     | Proximate Analysis (dry basis) |               |           |                                |
| 1   | Ash                      | 1.14%           | 4.96%     | 18.27%                         |
| 2   | Volatile matter          | 89.97%          | 77.00%    | 14.74%                         |
| 3   | Fixed Carbon             | 8.90%           | 18.04%    | 67.00%                         |
|     | Ultimate Analysis (dry basis) |               |           |                                |
| 5   | Carbon                   | 50.09%          | 39.29%    | 65.46%                         |
| 6   | Hydrogen                 | 6.11%           | 6.01%     | 1.23%                          |
| 7   | Oxygen (by different)    | 40.50%          | 48.79%    | 13.91%                         |
| 8   | Nitrogen                 | 1.98%           | 0.85%     | 1.14%                          |
| 9   | Sulfur                   | 0.18%           | 0.10%     | 0.00%                          |
| 10  | Ash                      | 1.14%           | 4.96%     | 18.27%                         |
| 11  | Total                    | 100.00%         | 100.00%   | 100.00%                        |
| 12  | HHV, MJ/kg (dry basis, as measured) |         |           | 16.32                           |
| 13  | LHV, MJ/kg (dry basis)   | 18.69           | 15.09     | 24.20                          |

Table 2. Typical composition of producer gas form gasification of wood pellet at UPS Merdeka 3 Depok.

| No. | Components | wood pellet, [8] | this work sample-1 | sample-2 |
|-----|------------|------------------|--------------------|----------|
| 1   | H2         | 21.62%           | 20.97%             | 14.64%   |
| 2   | CH4        | 2.30%            | 2.74%              | 1.73%    |
| 3   | CO         | 27.74%           | 13.11%             | 10.62%   |
| 4   | CO2        | 9.43%            | 18.75%             | 10.35%   |
| 5   | N2         | 38.91%           | 44.48%             | 62.60%   |
| 6   | LHV, kJ/Nm³ | 6333.5          | 4655.4             | 3364.7   |

3.2. Pellet Production Unit

The pellet production line consists of a chipping machine, a rotary dryer, a sieving machine, powdering machine, two pelleting machines. Design capacity and power consumption of these machineries are presented in Table 3. Weekly production rate must be scheduled carefully since the limited electricity from the PLN grid was only 40 kW. Assuming that all machineries could be operated at their design capacity, a weekly production rate of 9 ton might achieved (Table 3). The total electricity for running the machineries were 33 kW in day-1, -3 and -5. For day-2, -4 and -6, power consumption were 26 kW.

Unfortunately, the real capacity of both pellet machines were far from their design one, so this was a bottleneck to achieve the production rate of 9 ton/week. In the pelleting, woody biomass powder must be recycled in the pellet machine twice or three times to obtain a proper pelleting temperature of about 70°C in order to get the satisfied mechanical strength of pellet. Thus the real capacity of the pellet machines might only be half or one third of their design. Pellet with a good physical properties was also depended on the moisture content of the woody biomass powder, i.e. about 15 - 20%.
Table 3. Specification of machineries and production schedule for handling woody biomass of 9000 kg/week.

| No. | Combination equipment | Power (kW) | Design capacity (kg/h) | Operation time (h) | Day - |
|-----|-----------------------|------------|------------------------|-------------------|-------|
|     |                       |            |                        |                   | 1     |
|     |                       |            |                        |                   | 2     |
|     |                       |            |                        |                   | 3     |
|     |                       |            |                        |                   | 4     |
|     |                       |            |                        |                   | 5     |
|     |                       |            |                        |                   | 6     |
| Batch-1, woody biomass input 3 ton | | | | |
| 1. | chipping machine | 5.5 | 750 | 4.0 | 5.5 |
| 2. | rotary dryer | 11.0 | 500 | 5.9 | 11.0 |
| 3. | sieving machine | 1.5 | 700 | 3.8 | 1.5 |
| 4. | powdering machine | 7.5 | 400 | 6.6 | 7.5 | 7.5 |
| 5. | pellet machine, 6 mm | 7.5 | 120 | 10.9 | 7.5 | 7.5 |
| 6. | pellet machine, 8 mm | 11.0 | 300 | 4.4 | 11.0 |
| Total power, kW | | 44.0 | | 33.0 | 26.0 |

Batch-2, woody biomass input 3 ton

| No. | Combination equipment | Power (kW) | Design capacity (kg/h) | Operation time (h) | Day - |
|-----|-----------------------|------------|------------------------|-------------------|-------|
|     |                       |            |                        |                   | 1     |
|     |                       |            |                        |                   | 2     |
|     |                       |            |                        |                   | 3     |
|     |                       |            |                        |                   | 4     |
|     |                       |            |                        |                   | 5     |
| Batch-2, woody biomass input 3 ton | | | | |
| 1. | chipping machine | 5.5 | 750 | 4.0 | 5.5 |
| 2. | rotary dryer | 11.0 | 500 | 5.9 | 11.0 |
| 3. | sieving machine | 1.5 | 700 | 3.8 | 1.5 |
| 4. | powdering machine | 7.5 | 400 | 6.6 | 7.5 | 7.5 |
| 5. | pellet machine, 6 mm | 7.5 | 120 | 10.9 | 7.5 | 7.5 |
| 6. | pellet machine, 8 mm | 11.0 | 300 | 4.4 | 11.0 |
| Total power, kW | | 33.0 | 26.0 |

Batch-3, woody biomass input 3 ton

| No. | Combination equipment | Power (kW) | Design capacity (kg/h) | Operation time (h) | Day - |
|-----|-----------------------|------------|------------------------|-------------------|-------|
|     |                       |            |                        |                   | 1     |
|     |                       |            |                        |                   | 2     |
|     |                       |            |                        |                   | 3     |
|     |                       |            |                        |                   | 4     |
|     |                       |            |                        |                   | 5     |
| Batch-3, woody biomass input 3 ton | | | | |
| 1. | chipping machine | 5.5 | 750 | 4.0 | 5.5 |
| 2. | rotary dryer | 11.0 | 500 | 5.9 | 11.0 |
| 3. | sieving machine | 1.5 | 700 | 3.8 | 1.5 |
| 4. | powdering machine | 7.5 | 400 | 6.6 | 7.5 | 7.5 |
| 5. | pellet machine, 6 mm | 7.5 | 120 | 10.9 | 7.5 | 7.5 |
| 6. | pellet machine, 8 mm | 11.0 | 300 | 4.4 | 11.0 |
| Total power, kW | | 33.0 | 26.0 |

3.3. Economic Evaluation
The pellet production plant was installed in 2018, with a total investment cost of IDR 2,063,451,600. Using the price index of 711 in 2018 and 735 in 2020, an estimated investment cost in 2020 of IDR 2,132,989,995 was obtained (break down of cost are presented in Table 4). It is understandable that the self supporting electricity required more investment for the diesel generator (half of investment cost of pellet production machineries), even much higher for diesel generator and gasification system. Grants for diesel generators and gasification units are expected from the government or community services from companies.

There three scenarios concerning with supply of electricity, i.e (see figure 1): scenario-A, electricity grid (PLN), scenario-B, self supply using PLTD (diesel genset), and scenario-C, self supply using PLTD and gasification of pellet (integrated system). Parameters for estimating the manufacturing cost are presented in Table 5.
Table 4. Capital cost of wood pellet production unit at Depok

| No. | Parameter                                | estimated investment in 2020, IDR |
|-----|------------------------------------------|----------------------------------|
| 1.  | wood pellet production machineries       | 465,165,017                      |
| 2.  | gasification set unit                    | 237,751,009                      |
| 3.  | diesel engine and generator              | 236,717,308                      |
| 4.  | cooling Water system                     | 15,505,501                       |
| 5.  | power house                              | 25,842,501                       |
| 6.  | other utilities                          | 31,011,001                       |
| 7.  | Total Installed Cost (TIC)               | 1,011,992,336                    |
| 8.  | factory construction                     | 640,377,173                      |
| 9.  | land development (4% TIC)                | 40,479,693                       |
| 10. | Total Direct Cost (TDC)                  | 1,692,849,203                    |
| 11. | indirect cost (20% TDC)                 | 338,569,840                      |
| 12. | Capital Investment (FCI)                 | 2,031,419,043                    |
| 13. | working capital (5% FCI)                | 101,570,952                      |
| 14. | Total Capital Cost                      | 2,132,989,995                    |

Table 5. Assumptions for estimating direct manufacturing cost

| No | Parameters                        | Unit   | PLN grid | PLTD, diesel genset | PLTD and gasification |
|----|-----------------------------------|--------|----------|---------------------|-----------------------|
| 1  | woody biomass                     | kg/week| 9,000    | 9,000               | 9,000                 |
| 2  | woody biomass transportation cost | IDR/kg | 100      | 100                 | 100                   |
| 3  | pellet net products               | kg/week| 8,212    | 8,212               | 7,456                 |
| 4  | electricity consumption            | kWh/week| 675.5     | 675.5               | 675.5                 |
| 5  | electricity cost                   | IDR/kWh| 1,467.3  |                     |                       |
| 6  | diesel oil consumption            | L/week | 152.3    | 45.7                |                       |
| 7  | diesel oil price                  | IDR/L  | 9,400    | 9,400               |                       |
| 8  | pellets consumption               | kg/week|          | 756.3               |                       |
| 9  | cooling water price               | IDR/kWh| 23       | 38                  |                       |
| 10 | working time                      | h/day  | 6        | 6                   | 6                     |

Table 6. Direct manufacturing cost

| No. | Parameter                        | PLN grid | PLTD | PLTD and gasification |
|-----|----------------------------------|----------|------|-----------------------|
| 1.  | electricity cost                 | 991,161  |      |                       |
| 2.  | diesel oil cost                  | 1,431,620| 429,580|                       |
| 3.  | cooling water cost               | 15,536   | 25,669|                       |
| 4.  | Total, weekly production         | 1,891,161| 2,347,156| 1,335,249|
| 5.  | Annual direct cost (52 weeks)    | 98,340,372| 122,052,112| 69,432,948|
It is not surprising, that the direct manufacturing cost in the production using electricity from PLN grid was lower than that of using PLTD (see Table 6). This is understandable because electricity in PLN grid are mostly generated in coal fired power plant. On the other hand, self supporting electricity using the integration of PLTD and gasification (scenario-C) required a lowest direct manufacturing cost, since the cost of pellet for gasification feed was not taken into account.

**Table 7.** Fixed manufacturing cost.

| No. | Component | Amount | Total cost IDR/year |
|-----|-----------|--------|---------------------|
| 1.  | salary of manager *(based on Depok plant)* | 1 person | 36,000,000 |
| 2.  | salary of technicians *(based on Depok plant)* | 1 person | 36,000,000 |
| 3.  | salary of operator *(based on Depok plant)* | 6 person | 201,600,000 |
| 4.  | insurance and local taxes (7%FCI) | | 145,537,731 |
| 5.  | maintenance cost (2.5 % FCI) | | 51,977,761 |
| 6.  | Total fixed manufacturing cost | | 471,115,492 |

Based on the direct cost of production (Table 6), the self supporting electricity using PLTD-gasification (scenario-C) indicated the lowest costs. But the fixed manufacturing cost for all scenarios were the same (Table 7). The fixed manufacturing cost was much higher than those of direct manufacturing costs, and it took a large fraction of the total manufacturing cost. To reduce the fixed manufacturing cost, manpowers should be rearranged, for instance: a total of 4 persons in scenario-B and a total of 6 persons in scenario-C. Insurance and local taxes should be minimized or even excluded from the manufacturing cost since this project dealing with city waste management. Considering only direct and fixed manufacturing costs (Tables 6 and 7, respectively), calculated cost of pellets production (IDR/kg) would be 1333, 1389, and 1394 for scenarios-A, -B and -C respectively.

For economic analysis using Payback Period and Return on Investment, several assumptions were applied (Table 8). Calculated results for profitability of pellet production are presented in Table 9. In line with the aboved mentioned cost of production, these results of calculated profitability also indicated disadvantages of scenario-C compared to the other two scenarios.

**Table 8.** Assumptions for economic analysis.

| No. | Parameter | Unit | Value | Notes |
|-----|-----------|------|-------|-------|
| 1.  | pellets price | IDR/kg | 2,500 | market price in Depok region |
| 2.  | depreciation | IDR/year | 142,199,333 | linear |
| 3.  | equity capital structure | | 100% | government of Depok |
| 4.  | income tax | | 5% | tax for income less 4.8 billion IDR |
| 5.  | project period | year | 15 | |
| 6.  | distribution cost | IDR/ton | 100,000 | |
| 7.  | factory construction | year | 1 | 100% investment in year -1 |

**Table 9.** Results of calculation for profitability of pellet production.

| No. | Parameter | Scenario-A PLN grid | Scenario-B PLTD | Scenario-C PLTD and gasf. |
|-----|-----------|---------------------|-----------------|---------------------------|
| 1.  | gross profit, IDR | 455,401,736 | 431,689,996 | 389,960,360 |
| 2.  | net profit, IDR | 439,908,535 | 417,382,382 | 377,739,228 |
| 3.  | payback period, year | 4.8 | 5.1 | 5.6 |
| 4.  | return of Investment | 20.6% | 14.6% | 13.2% |
3.4. Life Cycle Analysis
Life cycle analysis was made based on ISO 14040. Assumptions for this study are presented in Table 10. The system boundary in this study is cradle to gate, as described in Figure 3. The goal in this study was to develop LCA model for wood pellet production using three different electricity sources and compare their impact to the environment.

Table 10. Assumptions for calculating CO$_2$ emission.

| No. | Parameter                                           | Unit       | Value | Notes |
|-----|-----------------------------------------------------|------------|-------|-------|
| 1.  | emission factor of diesel generator                 | kgCO$_2$/L | 2.697 | [9]   |
| 2.  | emission factor of coal power plant                 | kgCO$_2$/kWh | 1.05  | [10]  |
| 3.  | emission factor of transportation                    | kgCO$_2$/ton.km | 0.09  | [11]  |
| 4.  | substitution of diesel oil with producer gas         |            | 70%   | [12]  |
| 5.  | carbon closure                                       |            | 95%   | [13]  |
| 6.  | distance to land fill                                | km         | 10    | assumption |
| 7.  | radius of woody biomass collection                   | km         | 2     | assumption |

The CO$_2$ emissions for three scenarios of electrical energy sources are presented in Table 11 and Figure 2. For scenario A (electricity from PLN), the calculated CO$_2$ emission was the highest, i.e. 81.8 kgCO$_2$/ton woody biomass. The use coal as fuel in power plant has been known as a source of CO$_2$ emission [3]. Pellets production using scenario-B generated CO$_2$ emission of 45.6 kg CO$_2$/ton biomass. But it was unexpected that the use of integrated gasification and diesel generator set produced CO$_2$ higher than that of the scenario-B, due to addition process for converting biomass to gaseous fuels.

Table 11. CO$_2$ emission at capacity of 9000 kg/week.

| No. | Parameters                                           | Scenario-A PLN grid | Scenario-B PLTD | Scenario-C PLTD-gasf. |
|-----|-----------------------------------------------------|---------------------|-----------------|-----------------------|
| 1.  | type of fuel                                         | coal based          | diesel oil      | diesel fuel oil, producer gas |
| 2.  | woody biomass (kg)                                  | 9,000               | 9,000           | 9,000                 |
| 3.  | pellet product (kg)                                 | 8,212               | 8,212           | 7,454                 |
| 4.  | power electricity (kWh)                            | 675.5               | 675.5           | 675.5                 |
| 5.  | fuel consumption                                    |                     |                 |                       |
|     | a. diesel oil (L)                                   |                     |                 |                       |
|     | b. wood pellet (kg)                                 |                     |                 |                       |
| 6.  | CO$_2$ emission in transportation (kgCO$_2$/ton wood)| 1.6                 | 1.6             | 1.6                   |
| 7.  | CO$_2$ emission from process, (kgCO$_2$/ton wood)   | 81.8                | 45.6            | 66.5                  |
| 8.  | CO$_2$ emission from process taking into account the carbon closure of 95% (kgCO$_2$/ton wood) | 16.3               |                 |                       |

Since the production of gaseous fuel via gasification process consumed a type of biomass, the CO$_2$ emission might be re-evaluated with considering the carbon cycle [13]. Hence by taking a carbon closure of 95% into account, the calculated net CO$_2$ emission from the pellets production using scenario-C dropped to only 16.3 kgCO$_2$/ton of woody biomass.
Figure 2. CO$_2$ emission wood pellet production at capacity of 9000 kg/week.

Figure 3. CO$_2$ emission in wood pellet production with scenario-C at capacity of 9000 kg/week.
4. Conclusions
With a full capacity of 9 ton/week of woody biomass as a raw material, the most economically attractive for pellets production was using electricity from the PLN grid (scenario-A). In this case the calculated payback period was 4.8 year and RoI was 20.6%. However, this scenario of supplying electricity had a highest CO$_2$ emission of 81.8 kgCO$_2$/ton woody biomass. Although the use of integrated gasification process with diesel-genset (scenario-C) was not attractive economically, the CO$_2$ emission was very low, i.e. 16.3 kgCO$_2$/ton woody biomass. The following actions may improve the economic attractiveness of the pellets production with self supporting electricity by scenario-C: (i) lowering investment cost by using locally made gasification unit and building a low cost power house, (ii) employing right manpowers including managements, and (iii) reducing taxes and other administration cost.

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