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Biogas Generated from Palm Oil Mill Effluent for Rural Electrification and Environmental Sustainability

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Electricity is a catalyst for sustainable economic development. Electricity supplied by the national electricity grid is not accessible in remote areas and therefore alternative energy supply is highly needed for rural electrification. In Malaysia, 809 out of more than 10,000 schools had no access to 24-h electricity supply. Extension of grid electricity networks becomes uneconomical because of the geographical conditions of remote areas and the low electrical energy density demand of the population. Malaysia is the second biggest producer of palm oil in the world along with the palm oil mill effluent that can be converted to become a reliable energy source. The biogas generation from palm oil mill effluent (POME) in the rural areas could be effectively exploited to provide alternative source of energy for rural electrification. Currently, off-grid solar PV is used for providing alternative power in remote area due to the abundant solar energy resource in the region. Biogas from POME has mostly been used as fuel for on-site heating and power purposes. However, most of the palm oil mills in Malaysia produce more biogas than on-site demand. Due to logistic issue between biogas resource availability and its demand, biogas compression in gas cylinders is proposed for easy transportation in rural area. This paper presents a spatial optimisation approach for systematic design of biogas generated from POME for rural electrification. In this case study, alternative power from biogas generated from palm oil mill is pressurised up to 80 - 100 bar using compressor to run a gas engine coupled to a generator. Electricity generated from compressed biogas provide a better economic advantage and supply a more stable and sustainable energy source and could overcome the issue of intermittent resource of solar energy.

1. Introduction

In large mills, sterilization condensate, separator sludge (clarification) and hydrocyclone during oil palm milling processes are the main source of POME. In small mills, sterilization condensate and clarification are the main source of POME but not from hydrocyclone (Er et. al., 2011). For every ton of crude palm oil (CPO) processing, 3.05 m^3 of POME will be produced (Vijaya et. al., 2010). Clarification, sterilization and hydrocyclone units contribute to 60 %, 36 % and 4 % of POME (Wu et. al., 2010). In 2015, CPO produced was 19.96 million t which produced about 60.88 Mm^3 of POME (MPOB, 2015). As of June 2016, 50 palm oil mills employ tank type technologies to digest the POME and capture the released biogas while the other 36 use covered lagoon systems (Loh et.a, 2017). POME generated is pumped into extensive lagoons or tanks for treatment to meet the discharge standards prior to discharge into a nearby river or watercourse (UNFCCC, 2008). The current release of approximately 37,251 t of CO_2 annually into the atmosphere as a result of the anaerobic treatment of POME (Yoshizaki et. al., 2012).

Many recent researchers have been conducted to synthesise the optimal palm oil-based biorefinery network. Ng et. al. (2012) developed a generic model for optimal biorefinery synthesis with incorporation of heat integration analysis. An extended multi-objective approach of designing a palm oil-based biorefinery was then proposed by Kasivisvanathan et. al. (2012) for simultaneous optimising both economic and environmental aspects. Foo et. al. (2013) synthesised optimum EFB supply chain from palm oil mill clusters to optimally scaled CHP plants of associated power generators, while Chiew et. al. (2011) focused on optimal regional planning of

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CHP plant establishment (i.e. in terms of location and capacity planning) among different palm oil mill clusters in Selangor based on the geographical availability of EFB.

Currently, all palm oil mills are self-sufficient in terms of energy and steam. There is no apparent need for changing the current process, the mill tackles both issues of fuel requirement and waste disposal of biomass. However, this is far from the best practice possible as a number of improvements could be made for more sustainable and efficient utilization of biomass resources (Lam and Lee, 2011). Biogas compression increases energy density, reduces the storage requirements, and increases pressure to the level required to overcome resistance of gas flow. Bio compressed natural gas (BioCNG) for fuel transportation has been established in many developed countries such as Sweden, Germany etc. Biogas for fuel transportation usually compressed up to 250 bar and has strict requirements on its specification. Therefore biogas upgrading to remove H_2S, CO_2 and water is necessary for biogas for fuel transportation. In contrast, this paper presents the conversion of biogas from palm oil mill effluent (POME) into bio compressed natural gas (BioCNG) for rural electrification. CO2 comprises in biogas will not affect the internal combustion engine for electrification. However, without the separation of CO2 emission, the cost of biogas transportation will be increases. The trade-off with and without CO2 emission separation and the effect on cost will be examine through integrated spatial planning and optimisation. In previous works, typical pressure of 250 bar for bioCNG was used for fuel transportation. BioCNG and its optimum pressure and effect on cost of transportation for rural electrification has not yet been studied. In this paper, optimum pressure of BioCNG and biogas purification to meet spatial electrification demand at rural area will be studied.

2. Methodology

This section describes the model formulation for bioCNG for rural electrification.

2.1 Model formulation

The model formulation in this analysis considers transportation cost of BioCNG, purchased cost and operating cost of anaerobic digester, compressor, genset, biogas upgrading and BioCNG. The revenue of BioCNG was calculated by sales of electricity generated. This model also help in determining the amount of biogas supply required to meet certain energy demand. Economic benefit of biogas upgrading before compression was also assessed.

$$R_C = \frac{P_D}{P_{in}} \tag{1}$$

Eq (1) shows the formula of compression ratio.

$$V_D = \frac{V_{in}}{R_C} \tag{2}$$

Eq (2) represents the formula of discard volume after compression V_D. In this research, ideal gas behaviour is assumed.

$$E_{in} = 36 \, x \, 0.6 \, x \, V_{in} \tag{3}$$

Energy of biogas inlet is calculated by using Eq (3). The coefficient of 36 represents the energy content of pure methane and coefficient of 0.6 represents 60 % methane content of biogas for rough estimation.

$$E_{Truck} = \frac{V_{Truck}}{V_D} \, x \, E_{in} \, x \, R_C \tag{4}$$

Energy for one truck is calculated by Eq (4).

$$N_{Trip} = \frac{E_D}{0.4 \, x \, E_{Truck}} \, x \, 2 \tag{5}$$

Energy for one truck is used to calculate number of round trip required in Eq (5). Round-trip distribution is considered because of the reverse logistic of used gas cylinders. The coefficient of 0.4 represents the assumed electrical efficiency of gas engine technology to be 40 %.

$$C_{Trans} = D \, x \, X_D \, x \, N_{Trip} \, x \, T \tag{6}$$

Transportation cost is calculated by using Eq (6).

$$V_{AD} = 3.9139 \, x \, V_{in} \tag{7}$$

The volume of anaerobic digester is calculated by using Eq (7). Conversion of 1 t of POME treated to produce 28 m^3 of biogas and hydraulic retention time of 4 d are assumed to get the coefficient value of 3.9139 in Eq(7) (Kien-Yoo, 2002).

$$C_{AD} = \frac{1}{15}\ x\ 2.9\ x\ 10^5\ x\ (\frac{V_{AD}}{3800})^{0.7} \tag{8}$$

Purchased cost of anaerobic digester is then calculated by using Eq (8) (Yeoh, 2005).

$$BHP = 22\ x\ \frac{R_C}{Stage}\ x\ \#\ of\ stage\ \ x\ V_{in}\ x\ F \tag{9}$$

Eq (9) represents calculation of brake horsepower of compressor where F stands for coefficient of different number of stage compression.

$$C_C = \frac{1}{15}\ x\ \frac{M\&S}{280}\ x\ 517.5\ x\ BHP^{0.82}\ x\ 1.82 \tag{10}$$

Eq (10) calculates the purchased cost of compressor. M&S used in this study is 350.

$$C_{GS} = \frac{X_{CGS}\ x\ E_D}{15} \tag{11}$$

Eq (11) represents calculation of purchased cost of genset.

$$N_{GC} = \frac{V_{Truck}}{V_{GC}} \tag{12}$$

Number of gas cylinder required is calculated by using Eq (12).

$$C_{GC} = \frac{1}{15}\ x\ \frac{N_{Trip}}{2}\ x\ N_{GC}\ x\ X_{GC} \tag{13}$$

Number of gas cylinder required is used to calculate purchased cost of gas cylinder in Eq (13).

$$O_{AD} = 0.04\ x\ C_{AD} \tag{14}$$

$$O_C = 0.04\ x\ C_C \tag{15}$$

$$O_{GS} = X_{OGS}\ x\ E_D \tag{16}$$

$$O_{GC} = 0.04\ x\ C_{GC} \tag{17}$$

Eq (14) to Eq (17) show the OPEX of anaerobic digester, compressor, genset and repair/maintenance of gas cylinder respectively.

$$C_e = \frac{BHP\ x\ 0.746\ x\ T\ x\ X_e\ x\ 0.85\ x\ 1.0}{0.95} + \frac{BHP\ x\ 0.746\ x\ T\ x\ X_e\ x\ 0.15\ x\ 0.25}{0.90} \tag{18}$$

Eq (18) represents formula of electric utility cost of compression.

$$V_{Uin} = 0.6\ x\ \frac{1}{0.97}\ x\ V_{in} \tag{19}$$

$$V_{UD} = \frac{V_{Uin}}{R_C} \tag{20}$$

Eq (19) shows the different in biogas volume of inlet and outlet for biogas upgrading while Eq (20) without biogas upgrading. In biogas upgrading before compression, the volume of gas required to compress for meeting the same energy demand is lower compared to without biogas upgrading. Hence, brake horsepower of compressor is lower and that result in lower purchased and operating cost of compressor. Moreover, energy per truck increases because of the higher energy density in biogas upgrading before compression. This result in lesser number of round-trip required and the transportation cost is reduced. This also imply the purchased and repair/maintenance cost of BioCNG are reduced.

$$C_U = X_{CU}\ x\ V_{in} \tag{21}$$

$$O_U = X_{OU}\ x\ V_{in} \tag{22}$$

Despite the cost benefit of biogas upgrading discussed, biogas upgrading involves extra investment that is the CAPEX and OPEX represented by Eq (21) and Eq (22) respectively.

$$R_V = X_e\ x\ E_D \tag{23}$$

Eq (23) shows the calculation of the revenue from sales of electric generated by bottled biogas.

$$E_{eff} = 0.4\ x\ E_{in} \tag{24}$$

Eq (24) shows the calculation of effective energy supply. Eq (24) is used to determine the amount of biogas required to meet certain demand since the effective energy supply must be greater than the energy demand.

3. Case study

A case study of Rumah Dau, Sri Aman is selected to demonstrate the applicability of the model. This area consist of 114 population with 26 households and one school. The current rural electrification energy mix are solar energy, battery and diesel generator with capacity of 129.6 kWp, 48 v and 2 x 58 kW respectively. According to ETRC (2014), the average POME generated in Sri Aman is 216,000.00 m^3/y. Hence, BioCNG generated from POME is expected to replace the capacity of solar energy and diesel generator that have a total of 245.6 kW. The economic assessment is perform in this study.

4. Result and discussion

From the model formulated, the amount of biogas required to meet the energy demand of 245.6 kW is 86.5 m^3/h of biogas. By assuming one ton of POME can generate 28 m^3 of biogas (Loh et. al., 2014), a total of 27,930.53 m^3/y of POME is required to meet this energy demand. Sri Aman which has 216,000.00 m^3/y of average POME generated is able to supply enough POME for rural electrification. The demand area is approximately 35 km from palm oil mill. Figure 1 shows cost-benefit versus compression pressure for BioCNG without upgrading and figure 2 shows cost-benefit versus compression pressure for BioCNG with upgrading.

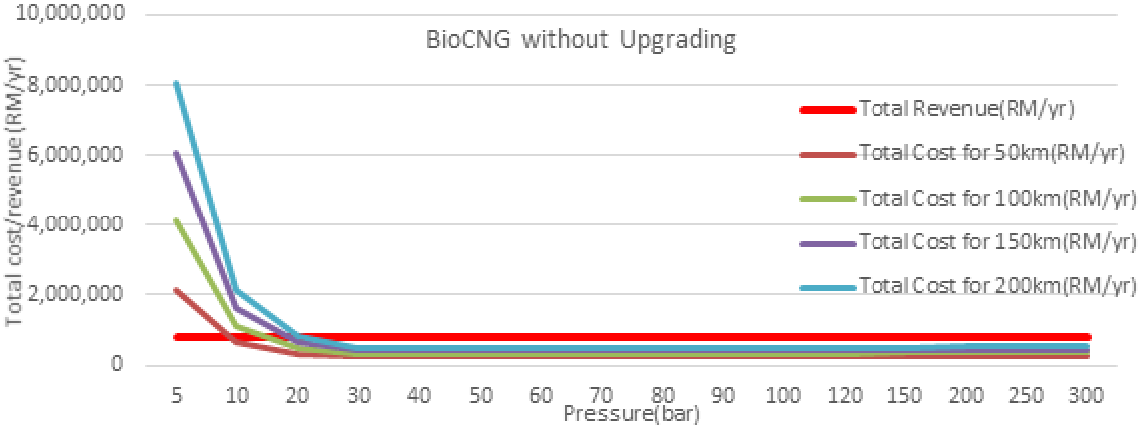

Figure 1: Cost-benefit versus compression pressure for BioCNG without upgrading

Figure 1 shows positive profit margin while figure 2 shows negative profit margin for biogas upgrading before compression. The total costs represent transportation cost, depreciated capital cost and utility cost. Figure 1 also demonstrates the relationship among total compression cost, revenue of BioCNG and compression pressure for various distance of electricity demand. The result of the finding shows that increase the storage compression of BioCNG will decrease the total cost due to lower transportation cost. Moreover, the decrease in transportation cost is more than the increase in compression utility cost as the pressure of BioCNG increases. This imply that biogas upgrading will make transporting the compressed biogas cylinder for rural electrification economically unattractive. Therefore in this work, removal of CO2 is not vital because it is not corrosive and its presence will not affect the calorific value of biogas and performance of internal combustion engine. Only H2S and water will be removed from the biogas prior to combustion in the gas engine. At 5 bar, the finding of the result shows that the cost of upgraded biogas for BioCNG is higher than the case of without upgrading at 50 km while the cost of upgraded biogas for BioCNG is lower than the case of without upgrading at 100, 150, and 200 km. This implies that transporting biogas without upgrading that contains high amount of CO_2 is not cost effective over long distance at 5 bar. This is due to higher transportation cost involved for compressed biogas without upgrading to meet the same energy demand. The extent is higher for longer distance. At higher pressure, the total cost is significantly reduced by compressing biogas to increase energy density of BioCNG. The energy per truck is greatly increased that will eventually reduce the transportation cost to meet the same energy demand. The travelling distance becomes less significant at higher pressure since the cost is almost the same.

In this work, the pressure for compressed biogas to produce electricity is significantly lower because the gas engine is normally operated at lower pressure at 250 – 300 mbar. However, there is a trade-off between the pressures with the volume of compressed biogas. At higher pressure, the energy density of BioCNG is more compared to lower pressure and cause lower cost of transportation to meet the same energy demand. The optimal pressure for BioCNG from biogas has been determined based on the trade-off with the total cost as illustrated in figure 1.

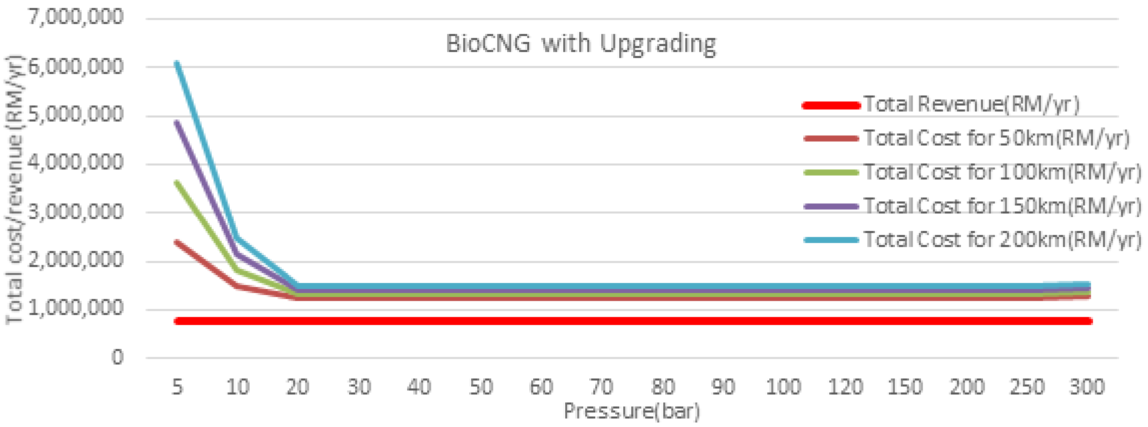

Figure 2: Cost-benefit versus compression pressure for BioCNG with upgrading

5. Conclusions

In conclusion, optimum pressure of compress biogas is selected to be 80 – 100 bar as further increase in storage pressure does not significantly increase the profit margin. In order to satisfy about 250 kW demand, it is found that use of compressed biogas can save up to MYR2.5 million as compared to hybrid of solar energy and diesel. It can be concluded that, electricity generated from BioCNG provide a better economic advantage and supply a more stable and sustainable energy source as compared to solar energy.

Nomenclature

BHP	Brake horsepower of compressor	O_U	OPEX of biogas upgrading (USD/y)
C_{AD}	Purchased cost of anaerobic digester (USD/y)	P_{in}	Suction pressure (bar)
C_C	Purchased cost of compressor (USD/y)	P_D	Discard pressure after compression (bar)
C_{GS}	Purchased cost of genset (USD/y)	R_C	Compression ratio
C_{GC}	Purchased cost of gas cylinder (USD/y)	R_V	Total revenue (USD/y)
C_U	Purchased cost of biogas upgrading (USD/y)	T	Operating days (d/y)
C_e	Electric utility of compression (USD/y)	V_{in}	Biogas inlet (m^3/h)
C_{Trans}	Transportation cost (USD/y)	V_D	Discard volume after compression (m^3/h)
C_T	Total cost (USD/y)	V_{Truck}	Biogas capacity per truck (m^3)
D	Travel distance from supply to demand (km)	V_{AD}	Volume of anaerobic digester (m^3)

E_{Truck}	Energy per truck (MJ/truck)	V_{GC}	Volume of gas cylinder (m^3)
E_{in}	Energy of biogas inlet (MJ/h)	V_{Uin}	Upgraded biogas inlet (m^3/h)
E_D	Energy demand (MJ/d)	V_{UD}	Discard volume of upgraded biogas after compression (m^3/h)
E_{eff}	Effective energy supply (MJ/d)	X_D	Cost parameter of transportation cost (USD/km)
N_{Trip}	Number of trips required	X_{CGS}	Capex parameter of genset (USD/kW)
N_{GC}	Number of gas cylinder	X_{GC}	Cost parameter of gas cylinder (USD/unit)
O_{AD}	OPEX of anaerobic digester (USD/y)	X_{OGS}	OPEX parameter of genset (USD/kW)
O_C	OPEX of compressor (USD/y)	X_e	Electric tariff (RM/kWh)
O_{GS}	OPEX of genset (USD/y)	X_{CU}	CAPEX parameter of biogas upgrading (USD•h/y•m^3)
O_{GC}	Repair/maintenance of gas cylinder (USD/y)	X_{OU}	OPEX parameter of biogas upgrading (USD•h/y•m^3)

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