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Mathematical Optimisation of Biogas Production and Utilisation

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Palm oil mill effluent (POME) is a source of biogas generation that can be a substitute for fossil fuel. High content of biological oxygen demand (BOD) and chemical oxygen demand (COD) of POME has the advantage to produce large amount of biogas through anaerobic digestion. The purpose of this research is to develop a mathematical model to determine the optimal process pathway of biogas, covering from the purification technology to mode of transportation and utilization. A hypothetical case study is conducted to run and test the model, in which different target location with different utilization mode was chosen. The model chose membrane separation of biogas, pipeline transportation to the targeted site, and electricity generation as the optimal pathway for biogas processing and utilization. Sensitivity analysis is performed to determine the impact of product price on the biogas process pathway selection. The sensitivity analysis revealed that the price of Bio-CNG has an impact on the model. Sensitivity analysis suggested the Bio-CNG sales price should be at least 10.4 USD/GJ to be economically feasible.

1. Introduction

Malaysia has shown good commitment to utilizing renewable energy. One of the major steps taken is to utilize oil palm biomass. It is expected that crude palm oil (CPO) is able to produce 1.95×10^7 t and possibly produce 5.85×10^7 m^3 of Palm Oil Mill Effluent (POME) waste yearly (MPOB, 2016). POME is a liquid effluent which is high in biological oxygen demand (BOD). Through anaerobic breakdown, it could produce up to 1.04×10^9 m^3 of biogas and generate 4.38 TWh/y of power (expecting 40 % gas engine productivity). POME has to be anaerobically digested to produce biogas and purified to remove unwanted gases such as hydrogen sulfide (H_2S), moisture, and carbon dioxide (CO_2) before it can be considered for utilization as fuel for power generation, as compressed natural gas (bio-CNG) or as liquefied natural gas (bio-LNG). The processed biogas is then transported to other points of utilization as palm oil mills are often located far away, estimated to be more than 10 km away from nearby towns. These factors lead to additional investment cost that prevents the investor from investing in biogas projects from POME for offsite utilization (Mohtar et al., 2017).

According to Figure 1, several purification technologies are available such as water scrubber, PSA, membrane separation, chemical absorption, and physical absorption. After purification, biogas is compressed for transportation. The final pressure of compression is dependent on the mode of transportation, either via truck (after bottling) or through pipeline. Options of biogas utilization include electricity generation and as bio-CNG for various application such as industrial heating, cooking, and fuel for natural gas vehicles. This study aims to develop a mathematical model to identify the optimal solution for purifying, transporting and utilizing biogas from POME for maximum profit.

Over the years, many studies have been done on biogas system optimization that deals with the mode of transportation, utilization, and demand. To optimize the production and investment plan for a biogas supply chain, a mathematical model was developed by Jensen et al. (2017) considering the mass and energy losses.

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Egieya et al. (2019) presented a generic mixed-integer linear programming (MILP) model for optimizing biogas supply network to generate electricity over monthly periods by maximizing profit. Another study developed a mathematical model to decide the locations for biogas plant, types and quantities of feedstock and products, size of land area for growing biomass, capacities of conversion technologies, inventories of feedstock and products, transportation modes and logistics (Zirngast et al., 2019). Galvez et al. (2015) proposed a mathematical model for reverse logistics and to optimize a proposed logistic network, ensuring the lowest cost and the shortest possible travelling distance. Díaz-Trujillo and Nápoles-Rivera (2019) presented a multi-objective optimization approach for biogas supply chain based on a superstructure to satisfy the biogas and bio-fertilizer demand in a Mexico region at the maximum profit and the minimum environmental impact. Sarker et al. (2019) formulated a mixed-integer non-linear programming (MINLP) model to optimally locate the feedstock collection hubs and bio-methane gas plants for minimum cost of operation.

Although many studies have been done on the biogas supply chain with nearby energy demands, none of these studies considers purification technology in the mathematical model. In this study, a mixed-integer linear programming (MILP) model is developed to include the selection of purification technology in biogas supply chain models. Further analysis is conducted to identify the Bio-CNG price to make biogas project from POME attractive for offsite utilization.

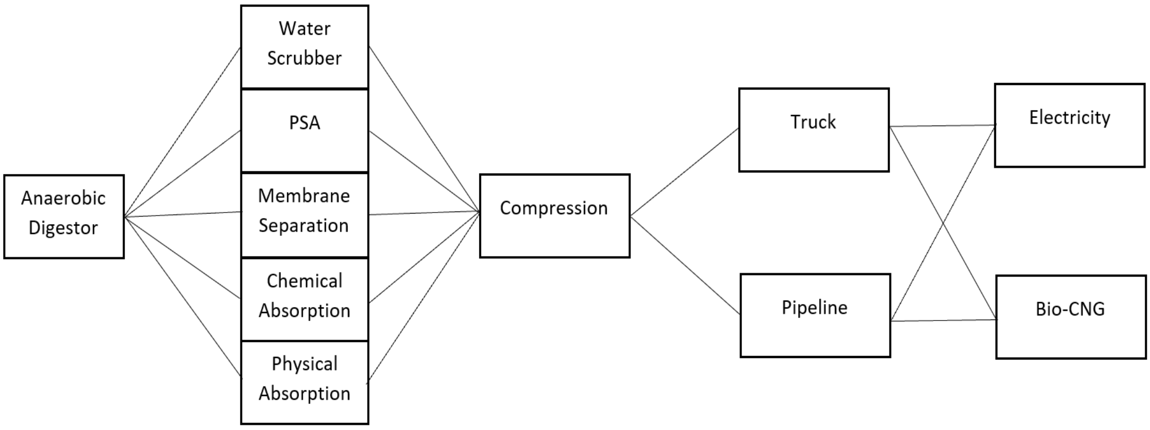

Figure 1: Superstructure of biogas process pathway

2. Mathematical formulation

This section describes the methodology of the work, which involves the formulation of mathematical model for optimization study. An optimization model contains an objective function, equality constraints and inequality constraints.

As mentioned in the introduction, the objective of this research is to identify the optimal pathway to utilize biogas generated from POME anaerobic digestion for maximum profit. The model presented is a MILP model. Eq(1) describes the objective of the model, which is to maximize the profit, z by subtracting the total cost (including compressor, transportation and purification cost), Totalcost from the sales revenue of biogas, Salesprice for different type utilization (electricity or bio-CNG).

$$max\, z = Salesprice - Totalcost \tag{1}$$

Several technologies for biogas purification are considered in this study. Eq(2) and Eq(3) are used to calculate the capital expenditure, PT_iCAPEX (USD/y) and operation expenditure, PT_iOPEX (USD/y) of purification technology. The biogas that has been purified is called biomethane. The capital expenditure is calculated by multiplying the equipment price, PT_iSP (USD/m^3/h) with biomethane processed, F_i (m^3/h). The operating expenditure is obtained by multiplying the unit operating and maintenance price of the purification technology, $O\&MPr_i$ (USD/kWh) with the energy consumption during each purification process, $ECon_{PT_i}$ (kWh/m^3) and biomethane processed, where LT is the number of operating hours in a year.

$$PT_iCAPEX = PT_i\, SP \times F_i \tag{2}$$

$$PT_iOPEX = (O\&MPr_{\ i} \times ECon_{PT_i} \times F_i) \times LT \tag{3}$$

The cost of compression is calculated using Eq(4) to Eq(8). The compressor price is obtained from a graphical correlation retrieved from Loh et al. (2002). Since the biomethane transported via pipeline and truck requires different pressure, the calculation of compressor cost is demonstrated using the biomethane with truck transportation, while the same procedure can be applied for pipeline transportation. The capital expenditure of compressor, Compressor CAPEX (USD/y) can be calculated using the purchase price of compressor, Compressor_j PurP (USD/m^3/h) and amount of biomethane after purification technology, BioV_T (m^3/h) as shown in Eq(4).

The operating cost of compressor, Compressor OPEX (USD/y) is calculated as shown in Eq(5). The operating cost is obtained by dividing energy consumption, Econ (kWh/h) and electric tariff, tariff (USD/kWh) by motor efficiency (%) and multiply with the total operating hours in a year. In this equation, it is assumed that the motor efficiency of the compressor is 95 %. Eq(6) presents the calculation for compressor adiabatic head, $H_{AD,T}$ (lbf/lbm), where R is the gas constant obtained by 1544 divided with the molecular weight of biomethane, T_1 is the inlet temperature in deg R, K is the specific heat ratio, P_1 is the inlet pressure in psia and $P_{2,T}$ is the pressure required for truck transportation in psia. Eq(7) converts the inlet flowrate from m^3/h to lb/min, where ρ_{CH4} (kg/m^3) is the density of biomethane. In Eq(8), the compressor power consumption is determined, where E_A is the adiabatic efficiency of the compressor.

$$Compressor\ CAPEX = Compressor_j\ PurP \times\ BioV_T \tag{4}$$

$$Compressor\ OPEX = \frac{ECon_T \times tariff}{\text{motor}\ efficiency} \times LT \tag{5}$$

$$H_{AD,T} = \frac{RT_1}{(K-1)/K}\left[\left(\frac{P_{2,T}}{P_1}\right)^{(K-1)/K} - 1\right] \tag{6}$$

$$W_T = \ BioV_T \times \rho_{CH_4} \times 0.0367437 \tag{7}$$

$$ECon_T = \frac{W_T H_{AD,T}}{33000\ E_A \times 1.3405} \tag{8}$$

In this study, two modes of biogas transportation are considered, which is transportation using the natural gas pipeline or via truck transportation. Eq(9) is the general equation for pipeline transportation cost, $\text{Transportation Cost}_P$ (USD/y), where Price_P (USD/MMBtu) is the unit pipeline cost and EBio_{Ack} (MMBtu/h) is the energy content of biomethane stream. In Eq(10), the energy content of biomethane was calculated using the heating value of biomethane, HV_{CH4} (MJ/kg), biomethane flowrate in pipeline, BioV_P (m^3/h), and density of biomethane, ρ_{CH4} (kg/m^3).

$$Transportation\ Cost_P = Price_P \times\ EBio_{ACk} \times LT \tag{9}$$

$$EBio_{ACk} = \frac{HV_{CH_4} \times BioV_P \times \rho_{CH_4}}{1055.87} \tag{10}$$

The transportation of biogas in truck is dependent on the volume of biogas, BioV_T (m^3) after compression process. The volume of biogas after compression, CompBioV_T (m^3/h) is determined using Eq(11). The number of trip required in a day, Number of Trip is identified using Eq(12) by dividing volume of biogas produced in a day by truck capacity, $\text{Truck}_{\text{capacity}}$ (m^3/truck). OPT represents the number of hours the plant is operating in a day. The time required per trip can be calculated using Eq(13), where Distance represents the transportation distance and Truck Speed is the mean travelling speed of the truck. The time lag represents time required for loading and unloading of products. Eq(14) computes the number of truck required where the time available represents the time available for transportation per truck per day.

The total cost for the truck purchase, TrCost_T (USD/y) can be calculated using Eq(15) where the total number of trucks is multiplied with the price per truck, TrPrice_T (USD/truck). Eq(16) is used to calculate the operation and maintenance cost of truck delivery, $\text{TrO\&M}_T$ (USD/y), where $\text{O\&MPrice}_T$ (USD/km) is the unit operating and maintenance cost per km travelled and OPD is the days of operation in a year.

$$CompBioV_T = BioV_T \frac{P_1}{P_{2,T}} \tag{11}$$

$$Number\ of\ Trip = \frac{CompBioV_T \times OPT}{Truck_{capacity}} \tag{12}$$

$$Time\ required\ per\ trip = \frac{Number\ of\ Trip \times 2 \times Distance}{Truck\ Speed} + Time\ Lag \tag{13}$$

$$Number\ of\ Truck = \frac{Number\ of\ Trip \times Time\ required\ per\ trip}{Time\ available} \tag{14}$$

$$TrCost_T = Number\ of\ Truck\ \times\ TrPrice_T \tag{15}$$

$$TrO\&M_T = O\&MPrice_T \times Number\ of\ Trip\ \times\ 2 \times Distance\ \times OPD \tag{16}$$

Eq(17) shows the calculation for total capital cost throughout project lifetime, while Eq(18) computes the annual operating cost of the system. Eq(19) shows the calculation for annual cost of biogas production, where AF is the capital recovery factor.

$$Total\ Capex = \sum_i PT_i CAPEX + Compressor\ CAPEX + TrCost_T \tag{17}$$

$$Annual\ Opex = \sum_i PT_i OPEX\ + Compressor\ OPEX + Transportation\ Cost_P + TrO\&M_T \tag{18}$$

$$Totalcost = TotalCapex \times AF + Annual\ Opex \tag{19}$$

Following total cost calculation is sales price calculation for each utilization options. The option includes domestic cooking, industrial heating, natural gas vehicle (NGV), natural gas grid and electricity. Bio-CNG is used for domestic cooking, industrial heating, NGV and natural gas grid. The sales revenue of bio-CNG, $Salespr_{BioCNG}$ (USD/y) and electricity, $Salespr_{Elec}$ (USD/y) is calculated using Eq(20) and Eq(21). The price of Bio-CNG, Price of BioCNG(USD/MJ) is multiplied with the total biomethane demand, Bio_{demand} (m^3/h), heating value of methane, HV_{CH4} (MJ/kg) and density of methane to obtain the total price. The sales revenue of electricity is determined by multiplying the total biomethane demand for electricity, $Bio_{Electricity}$ (m^3/h), heat rate, HR (kWh/MJ), heating value of methane, density of methane, the Feed-in-Tariff value, FiT (USD/kWh) and the annual operating hours. Eq(22) computes the total sales revenue per year.

$$Salespr_{BioCNG} = HV_{CH_4} \times \rho_{CH_4} \times\ Price\ of\ BioCNG \times\ Bio_{demand} \times LT \tag{20}$$

$$Salespr_{Elec} = HR \times HV_{CH_4} \times \rho_{CH_4} \times FiT \times Bio_{Electricity} \times LT \tag{21}$$

$$Salesprice = Salespr_{BioCNG} + Salespr_{Elec} \tag{22}$$

The calculation for annual profit and simple payback period is shown in Eq(23) and Eq(24). Annual profit is obtained by the subtraction of annual operating cost from the annual sales. The simple payback period can then be computed by dividing the total capital cost with the annual profit.

$$Annual\ Profit = Salesprice - Annual\ Opex \tag{23}$$

$$Simple\ Payback = \frac{Total\ Capex}{Annual\ Profit} \tag{24}$$

The volumetric balance (equality constraints) for this model is shown through Eq(25) to Eq(27). Eq(25) indicates that the total amount of biogas available at the start has to be equal to the total volume of biogas sent to each purification technology. Eq(26) shows that all purified biogas is to be transported via truck or pipeline to utilization. Eq(27) indicates that the processed biogas is either used to generate electricity or used as Bio-CNG.

$$F_{Biogas} = \sum_i F_i \tag{25}$$

$$\sum_i F_i = BioV_P +\ BioV_T \tag{26}$$

$$BioV_P +\ BioV_T = Bio_{Electricity} +\ Bio_{demand} \tag{27}$$

3. Case study and data collection

In order to show the applicability of the model, a hypothetical case study is performed to obtain the optimal biogas process pathway. In this research, Pasir Gudang district in Johor is taken as a case study. The estimated biomethane production from POME based on CPO production of local palm oil mill located in Pasir Gudang is 2.3 ×10^6 m^3/y (Chin et al., 2013). The COD level in POME is 51 g/L (Zainal et al., 2017). Methane heating value is 50 MJ/kg and density is 0.656 kg/m^3.

The other data for this research is extracted from different sources. Among required data are capital cost (CAPEX) and operating and maintenance cost (OPEX) of purification technology, transportation mode (truck and pipeline), and compressor. The distance from identified locations to substations, sales price of Bio-CNG, sales price of electricity, FiT, electricity tariff and capital recovery factor should also be identified.

For purification technology, the CAPEX for water scrubber is 3,333 USD/m^3/h, pressure swing absorption is 5,888 USD/m^3/h, membrane separation is 2,824 USD/m^3/h, chemical absorption is 3,298 USD/m^3/h and physical absorption is 3,040 USD/m^3/h. The operating and maintenance cost of water scrubber is 4.74 × 10^{-3} USD/kWh, pressure swing absorption is 3.38 × 10^{-3} USD/kWh, membrane separation is 1.57 × 10^{-3} USD/kWh, chemical absorption is 1.82 × 10^{-3} USD/kWh and physical absorption is 2.46 × 10^{-3} USD/kWh. For the energy consumption of the separation unit, the energy requirement for water scrubber is 0.2 kWh/m^3, pressure swing absorption is 0.23 kWh/m^3, membrane separation is 0.12 kWh/m^3, chemical absorption is 0.15 kWh/m^3 and physical absorption is 0.22 kWh/m^3.

As for the compressor, the purchase price of compressor is 276 USD/m^3/h. The tariff used to operate the compressor is taken as 0.09 USD/kWh. The adiabatic efficiency is assumed as 70 %. The biomethane at inlet has a molecular weight of 19 kg/kmol, specific heat ratio of 1.3, initial temperature of 536.67 deg R and initial pressure of 14.7 psia. The final pressure required for truck and pipeline transportation are 2900 psia and 290 psia.

For transportation, the truck capacity is 30 m^3 per truck. Price of truck is 34,554.35 USD and operating and maintenance cost is 0.09 USD/km. The truck is assumed to travel at 70 km/h and is working 8 hours a day. The loading and unloading time is assumed as 2 hours. For pipeline transportation, it is assumed that the gas pipeline will be constructed by Gas Malaysia and the user are required to pay 0.45 USD/ MMBtu to use the facility.

Sales price of Bio-CNG is 8.68 USD/GJ and electricity generated from biogas is 0.077 USD/kWh. The power plant is assumed to have a heat rate of 0.1206 kWh/MJ.

In this case study, different target locations are chosen to supply biogas. There are several targeted locations identified within Pasir Gudang that could utilize energy from POME biogas. The total distance to all these locations from the palm oil mill is 33.6 km. The lifetime of the project is assumed as 25 y and capital recovery factor of 0.071. The plant is assumed to be working 24 hours a day and 365 days a year.

4. Result and discussion

This section discusses the mathematical optimization result, where the optimal biogas supply pathway with the greatest profit will be determined. Sensitivity result is also conducted to investigate the effect of Bio-CNG price on the optimal biogas supply pathway.

4.1 Biogas process pathway optimization

The problem is coded in the software General Algebraic Modelling System (GAMS), version 24.7 (GAMS, 2016), where the solver CPLEX is used to solve the associated mixed-integer linear programming problem (MILP). The results obtained from GAMS shows that the objective to optimize the net profit is 6.51 ×10^5 USD/y. The cost for membrane separation is 5.69 ×10^4 USD/y, with a CAPEX of 7.40 ×10^5 USD and OPEX of 4.41×10^3 USD/y. The pipeline cost is 3.21×10^4 USD/y with electricity sales of 7.77 × 10^5 USD/y. The optimal pathway of biogas production, transportation and utilization is by using membrane separation as purification technology, pipeline as the transportation mode to transport biogas to the targeted distribution centre and utilizing it in the form of electricity. From the optimization result, the payback period for the offsite project is identified as 1.15 y. Membrane separation is chosen as a profitable purification technology because it has a number of merits, including low cost, high energy efficiency and involves a simple process (Sun et al., 2015). This technology allows H_2S, CO_2 and H_2O to pass through the membrane while retaining CH_4 on the inlet side. Pipeline transportation is chosen in this optimization because for truck transportation, the average capacity of a truck ranges from 30-60 m^3. In order to transport biogas in higher scale, more trucks will be required and considering fuel, operating and maintenance cost of each trip, opting for truck will not be profitable. For utilization, electricity is chosen in the mathematical optimization because in Malaysia there is already a FiT scheme for the usage of biogas as electricity while other source does not have financial aids or subsidy in place. To investigate the suitable rate of subsidy for Bio-CNG, sensitivity analysis is conducted in the following section by varying the price of Bio-CNG and analyzing the outcome.

4.2 Bio-CNG subsidy

The result obtained did not recommend the utilization of biogas as Bio-CNG as its selling price is less profitable than the electricity. This suggests the need for financial aid to make the Bio-CNG utilization more feasible. In this section, an analysis is conducted to determine the subsidy required for offsite Bio-CNG as shown in Table 1. Based on Table 1, it can be seen that only when the Bio-CNG sales price increases to 10.4 USD/GJ that the model chooses Bio-CNG utilization as the most optimal option for maximum profit.

Table 1: Analysis on different prices of Bio-CNG

Sales price of Bio-CNG (USD/GJ)	FiT (USD/y)	Chosen utilization option
8.68	0.077	Electricity
9.8	0.077	Electricity
10.4	0.077	Bio-CNG

5. Conclusions

Malaysia has a high potential to develop biogas industry due to the abundance of POME as a biogas source. Most of these resources are now under-utilized and the analysis shows that the Malaysian Government needs to provide more incentive to boost biogas from POME development in the country. The model presented in this study has seen to be capable to optimize the cost of a POME biogas system that takes into account purification technologies, transportation modes, and utilization options. Through this study, the net profit of the biogas project is determined as 6.51 $\times 10^5$ USD/y with payback period of 1.15 y. The optimal biogas processing and utilization pathway involves the membrane separation of raw biogas, pipeline transportation to desired sites, and generation of electricity using biogas. This model is beneficial for energy engineers, and energy policymakers to plan for future energy developments. In the future, a more detailed study will be conducted including the specific energy demand that is required by the nearby towns and spatial analysis.

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