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Optimising Process Pathway for Palm Oil Mill Effluent to Compressed Biomethane Off-Site Utilisation

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The palm oil mill effluent (POME) is a high-strength wastewater as characterised by its high biological oxygen demand and chemical oxygen demand. Through anaerobic digestion, it can be valorised into biogas to serve as sustainable substitution for fossil fuel. In order to fully exploit the potential of POME as sustainable source for renewable energy, the optimisation of the supply-demand chain that covers biogas production, biogas purification to biomethane, biomethane transportation and biomethane off-site utilisation, is crucial for understanding its economical-technical performance. There are many works that had explored the pathway for compressed biomethane (CBM) production, this work further the investigation by including consideration on pressure changes and requirement across the pathway and subsequently identifies suitable incentive rate to improve the economic performance. In this study, a mathematical model to determine the optimal process pathway was developed based on a mixed integer programming model and solved using General Algebraic Modeling System. The model showed that the optimal pathway would result in a payback period of 6 y, with a total capital investment cost of USD 2,934,564. The biomethane off-site utilisations were illustrated through electricity generation and CBM. The sensitivity analysis on Feed-in-Tariff further showed that a rate at USD 0.116 kWh was economically desirable. For CBM, the sales price should be at least USD 8.2-12.9 /MMbtu.

1. Introduction

The palm oil industry is the key economic sector for Malaysia. In year 2021, the crude palm oil (CPO) production reached 18.12 Mt (MPOB, 2022). It is estimated that 5-7.5 m^3 of water are required to produce 1 t of CPO, where more than 50 % ended up as wastewater known as the palm oil mill effluent (POME). On this basis, it was estimated that 50-75 Mm^3 POME can be generated annually (Foong et al., 2020). POME is characterised by high chemical oxygen demand (COD) (44,300 – 102,691 mg/L), high biological oxygen demand (BOD) (25,000 – 65,714 mg/L) and low pH (3.4 – 5.2) (Chin et al., 2013). A COD/BOD ratio of 0.5 indicates its high organic matter content that is suitable for biological processes.

POME is treated conventionally by open-ponding system in Malaysia. Despite its lower operation and maintenance cost, the open ponding system neither capture greenhouse gas from organic matter decomposition nor offer resource recovery option. Anaerobic digestion (AD) is a cascade of biological reactions where the organic matter is degraded under the absence of oxygen. The process consists of four main steps, name hydrolysis, acidogenesis, acetogenesis and methanogenesis. The end-products are CH_4-rich biogas and nutrient-rich digestate. The AD system offers a greener and profitable alternative. The supply-demand chain for POME-to-biomethane off-site utilisation can be covering POME acquisition, AD of POME for biogas production, biogas purification for biomethane, compression of biomethane for transportation and off-site utilisation.

During the AD of POME, the biogas produced generally contain 55 - 65 % CH_4. A purification unit can help to enrich the biogas to biomethane with up to 95 - 98 % CH_4 purity (Yousef et al., 2018). This could involve process units such as chemical adsorption, pressure swing adsorption and scrubber that could remove CO_2

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and H_2S. Current dominant purification options are water scrubbing and pressure swing adsorption (Wang et al., 2015). Purified biomethane which then undergoes a compression at a pressure of 200 bar is known as compressed biomethane (CBM). CBM can ease the transportation logistic as it can be bottled and delivered by truck or injected into a natural gas pipeline. It can then be used for off-site utilisation such as electricity generation or CBM as fuel.

The palm biomass industry is affected by three factors, which are consistent supply, process efficiency, and market demand and price (Tang et al., 2015). The optimisation of the POME valorisation network had been presented in several studies. Lee et al. (2019) conducted a spatial planning for the virtual distribution of CBM, which is produced from POME, to meet industrial energy demand. An optimisation model was formulated to minimise the total cost of energy supply for the demand location. On another study, Galvez et al. (2015) optimised the logistic network to reduce the cost for waste collection and biomethane production using a mixed integer linear programming. Khishtandar (2019) performed a non-linear programming optimisation model to minimise the total cost of biomethane supply chain by optimising the reactor location and biomass transportation. Lauven et al. (2019) also developed a MILP optimisation model to maximise the revenues from power sales through optimising hourly production schedules. Mohtar et al. (2021) has developed a LP optimisation model to identify the optimal pathway however it did not consider pressure changes across the operating units.

Changes in pressure will affect the selection of technology for biomethane production as purification unit that operates at a higher pressure will not require further compression before delivery, hence additional equations on compression are included to improve the model. Another research interest is the suitable incentive rate for the off-site biomethane utilisation as electricity or CBM to improve the economic performance. This study aims to optimise the off-site utilisation of biomethane generated from the AD of POME via mathematical modelling, with consideration of the optimal pathway for biogas purification (i.e. water scrubber, pressure swing adsorption, membrane separation, chemical adsorption and physical absorption), biomethane compression and transportation (i.e. pipelines injection and trucks transportation) and for off-site utilisation (i.e. electricity generation and CBM). Sensitivity analysis on the cost factor for biomethane off-site utilisation, which are incentive for CBM and impact of distance on pressure requirement are also carried out. It is envisioned that the outcome of the study could facilitate decision making in selecting the process units and logistic operation by considering the trade-off between economic and process performance. The outcome can recommend desirable government incentive and policy for enabling an economically sound POME to biomethane utilisation business model.

2. Methodology

2.1 Problem formulation and superstructure construction

This project considers the off-site utilisation of biomethane produced from palm oil mill. The biomethane produced is generally in excess of the demand at the mill and needs to be stored and transported for off-site usage. The raw biogas from AD of POME would undergo purification and compression units to become compressed biomethane (CBM) to be transported, either by truck or pipeline, for off-site usage. The superstructure for POME to biomethane off-site utilisation is illustrated in Figure 1.

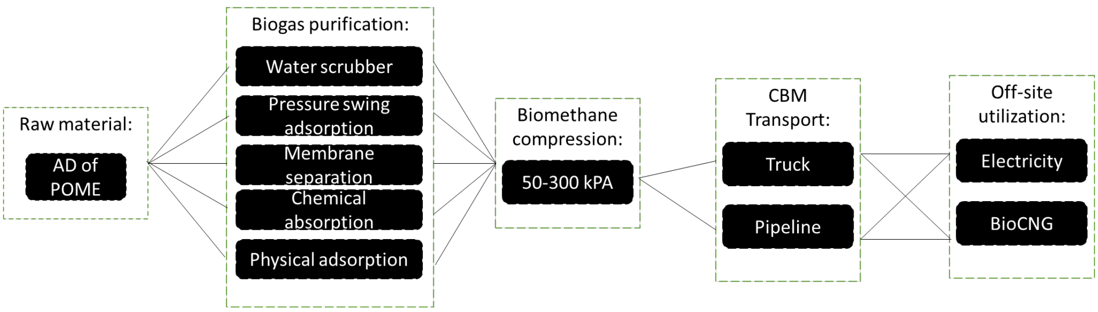

Figure 1: POME to biomethane off-site utilisation superstructure

2.2 Data collection and mathematical model development

The input data used in the project is based on five main processes. (1) System information, which consists of parameters like the CPO production, POME generation, biomethane production, operation period, system lifespan and interest rate. (2) Purification unit, which came with four options of water scrubbing (WS), pressure swing adsorption (PSA) membrane separation (MS) and chemical adsorption (CA). The parameters considered were pressure, capital cost, operating cost, CH_4 slip, CO_2 removal, biomethane recovery efficiency and lower heating value. (3) Compression unit, with options of varying compressor capacity of 50-300 kW for pipeline injection and truck transportation. The parameters for pipeline injection include capital cost, operating cost, initial pressure, final pressure and power consumption initial pressure. The parameters for truck transportation are capital cost, operating cost, final pressure and power consumption. (4) Transportation, the parameters for pipeline injection includes transportation pressure, pipeline capital cost and operating cost where for truck transportation, the parameters are truck speed, truck capacity, truck price, fuel efficiency, fuel cost, loading time, working time at truck pressure of 100 - 250 bar. (5) Product utilisation, with parameters like compressed biomethane pressure and price, power plant heat rate, plant capital cost, fixed operating cost and variable operating cost, and feed-in-tariff rate. The mathematical model for this study can be found in Mohtar et al. (2021), this study improves the model by including a more detailed formulation on compression.

The purified biomethane, F_{pr}^{Out} will be compressed for transportation, either through trucks or pipeline as indicated in Eq(1). Eqs(2) and (3) that the biomethane transported via pipeline, $F_{pr}^{Comp.pipe}$ and truck, $F_{pr}^{Comp.truck}$ will be used for CBM ($F_{pr}^{Pipe,cng}$, $F_{pr}^{Truck,cng}$) or electricity ($F_{pr}^{Pipe,elec}$, $F_{pr}^{Truck,elec}$) demand.

$$F_{pr}^{Out} = F_{pr}^{Comp.pipe} + \sum_t F_{pr,t}^{Comp.truck} \qquad \forall pr \tag{1}$$

$$F_{pr}^{Comp.pipe} = F_{pr}^{Pipe,elec} + F_{pr}^{Pipe,cng} \qquad \forall pr \tag{2}$$

$$\sum_t F_{pr,t}^{Comp.truck} = F_{pr}^{Truck,elec} + F_{pr}^{Truck,cng} \qquad \forall pr \tag{3}$$

As different purification unit has outlet at different pressures, the compressor stage requirements for electricity and CBM using pipeline ($Comp.Stage_{pr}^{Pipe}$, $Comp.Stage_{pr}^{Pipe2}$) and truck ($Comp.Stage_{pr,t}^{Truck}$, $Comp.Stage_{pr,t}^{Truck2}$) can be determine using Eqs(4) to (7), with P^{pr}, P^{pipe} and P^{Truck} and P^{CNG} indicate the initial pressure of biomethane, pressure required for pipeline and truck transportation and pressure required for CBM utilisation.

$$Comp.Stage_{pr}^{Pipe} = cell\frac{Log\,\frac{P^{pipe}}{P^{pr}}}{Log\ (Maximum\ Compression\ Ratio)} \tag{4}$$

$$Comp.Stage_{pr,t}^{Truck} = cell\frac{Log\,\frac{P^{Truck}}{P^{pr}}}{Log\ (Maximum\ Compression\ Ratio)} \tag{5}$$

$$Comp.Stage_{pr}^{Pipe2} = cell\frac{Log\,\frac{P^{CNG}}{P^{pipe}}}{Log\ (Maximum\ Compression\ Ratio)} \tag{6}$$

$$Comp.Stage_{pr,t}^{Truck2} = cell\frac{Log\,\frac{P^{CNG}}{P^{Truck}}}{Log\ (Maximum\ Compression\ Ratio)} \tag{7}$$

The compressor energy consumption for pipeline ($Comp_{pr}^{Econs,Pipe}$, $Comp_{pr}^{Econs,Pipe2}$) and truck ($Comp_{pr,t}^{Econs,Truck}$, $Comp_{pr,t}^{Econs,Truck2}$) for utilisation as electricity and CBM can be calculate using Eqs(8) to (11).

$$Comp_{pr}^{Econs,Pipe} = \frac{Z\frac{MW}{3600}\,R\,T_{in}\,\frac{Comp.Stage_{pr}^{Pipe}}{Comp_{eff}}\,\frac{k}{k-1}\,\frac{p^{pipe}}{p^{pr}}^{\left(k-\frac{1}{Comp.Stage_{pr}^{Pipe}.k}\right)-1}}{density_{Biomethane}} \tag{8}$$

$$Comp_{pr,t}^{Econs,Truck} = \frac{Z\frac{MW}{3600}\,R\,T_{in}\,\frac{Comp.Stage_{pr,t}^{Truck}}{Comp_{eff}}\,\frac{k}{k-1}\,\frac{p^{Truck}}{p^{pr}}^{\left(k-\frac{1}{Comp.Stage_{pr,t}^{Truck}.k}\right)-1}}{density_{Biomethane}} \tag{9}$$

$$Comp_{pr}^{Econs,Pipe2} = \frac{Z\frac{MW}{3600}\,R\,T_{in}\,\frac{Comp.Stage_{pr}^{Pipe2}}{Comp_{eff}}\,\frac{k}{k-1}\,\frac{p^{CNG}}{p^{pipe}}^{\left(k-\frac{1}{Comp.Stage_{pr}^{Pipe2}.k}\right)-1}}{density_{Biomethane}} \tag{10}$$

$$Comp_{pr,t}^{Econs,Truck2} = \frac{Z\frac{MW}{3600}\,R\,T_{in}\,\frac{Comp.Stage_{pr,t}^{Truck2}}{Comp_{eff}}\,\frac{k}{k-1}\,\frac{p^{CNG}}{p^{Truck}}^{\left(k-\frac{1}{Comp.Stage_{pr,t}^{Truck2}.k}\right)-1}}{density_{Biomethane}} \tag{11}$$

The compressor power requirement for pipeline ($Comp_{pr}^{Power,Pipe}$) and truck ($Comp_{pr,t}^{Power,Truck}$) can be calculated using Eqs(12) and (13). Eqs(14) and (15) represent the compression of transported biomethane to meet the required pressure of CBM using pipeline ($Comp_{pr}^{Power,Pipe2}$) and truck ($Comp_{pr,t}^{Power,Truck2}$).

$$Comp_{pr}^{Power,Pipe} = F_{pr}^{Comp.pipe} Comp_{pr}^{Econs,Pipe} \qquad \forall pr \qquad (12)$$

$$Comp_{pr,t}^{Power,Truck} = F_{pr,t}^{Comp.truck} Comp_{pr,t}^{Econs,Truck} \qquad \forall pr, t \qquad (13)$$

$$Comp_{pr}^{Power,Pipe2} = F_{pr}^{Pipe,cng} Comp_{pr}^{Econs,Pipe2} \qquad \forall pr \qquad (14)$$

$$Comp_{pr,t}^{Power,Truck2} = F_{pr}^{Truck} Comp_{pr,t}^{Econs,Truck} \qquad \forall pr, t \qquad (15)$$

The number of compressor required for electricity and CBM utilisation through pipeline ($N_{pr,c}^{Comp.Pipe}$, $N_{pr,c}^{Comp.Pipe2}$) and truck ($Comp_{pr,t}^{Power,Truck}$, $Comp_{pr,t}^{Power,Truck2}$) transportation can be determined through Eqs(16), to (19) where the total installed capacity, $CompcCap$ should be greater or equal to the required capacity.

$$Comp_{pr}^{Power,Pipe} \leq \sum_{c} N_{pr,c}^{Comp.Pipe} Comp_{c}^{Cap} \qquad \forall pr \qquad (16)$$

$$Comp_{pr}^{Power,Pipe2} \leq \sum_{c} N_{pr,c}^{Comp.Pipe2} Comp_{c}^{Cap} \qquad \forall pr \qquad (17)$$

$$Comp_{pr,t}^{Power,Truck} \leq \sum_{c} N_{pr,t,c}^{Comp.Truck} Comp_{c}^{Cap} \qquad \forall pr, t \qquad (18)$$

$$Comp_{pr,t}^{Power,Truck2} \leq \sum_{c} N_{pr,t,c}^{Comp.Truck2} Comp_{c}^{Cap} \qquad \forall pr, t \qquad (19)$$

The objective function, variable, parameter and constrain are encoded in GAMS version 23.7. The objective function set to this model is to maximise the gross profit of the biomethane supply chain by determining the optimal modes of purification, compression, transportation, and utilisation based on the cost parameters provided. CPLEX solver is applied for optimising the mixed integer linear programming model. Sensitivity analysis is then performed by varying the feed-in-tariff (FiT) rate and CBM selling price. The base rate for the FiT is based on biogas FiT rate in 2021, which was RM 0.3184/kWh (~USD 0.077) (SEDA, 2021). For CBM, the base rate is based on the CBM price in 2021, which was 5.35 USD/MMBtu (EIA, 2021).

3. Results and discussions

3.1 Process performance at selected optimal pathway

Based on the model output, the optimal purification unit selected was membrane separation (MS) with over 100 km travel distance. Under the optimal scenario, the total cost for the process chain was USD 586,320 /y. The cost breakdown showed that purification cost accounted for the highest, which was 66 % of the total cost, followed by power plant with 25 %, truck cost with 5 % and compression cost with 4 %. The electricity sales were calculated to be USD 839,366 /y with an electricity generation of 3,326,632.8 kWh. The gross profit was USD 253,046 /y. The payback period was calculated to be around 6 y (i.e. 5.81 y).

3.2 Sensitivity analysis

It is worth to explore on the deterministic factors that could favour a shorter payback period to make this valorisation pathway for economically attractive. The two cost-affecting factors selected were based on the biomethane off-site utilisation: (1) feed-in-tariff rate for electricity generation and (2) selling price of CBM.
Based on a scenario of 100 km travel distance and 4,200,000 m^3/y of raw biomethane available, a sensitivity analysis was carried out with a feed-in-tariff rate ranging from USD 0.07 - 0.16 /kWh. The effect of feed-in-tariff rate on the payback period is presented in Figure 2. To become an attractive investment where the payback period is within 3 y, the feed-in-tariff will need to be increased up to USD 0.116 USD/kWh.

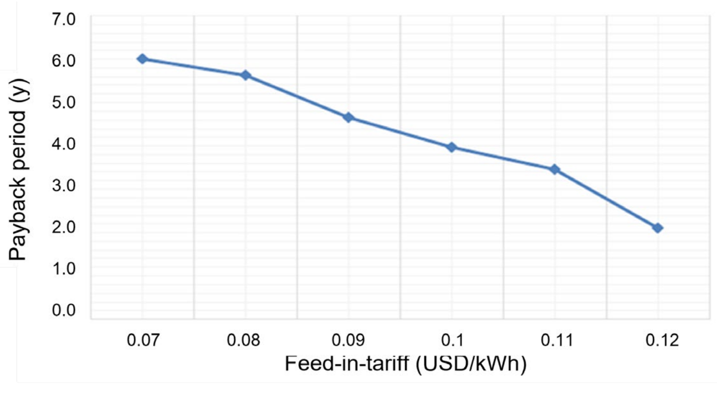

Figure 2: Payback period (y) based on different Feed-in-tariff rate (USD/kWh)

The model did not select bioCNG CBM off-site utilisation as an optimal option. To investigate further, the model was run with the utilisation option limited to bioCNGCBM by zeroing the value of flowrate of biomethane to be used for electricity generation. The model showed that the annual gross profit was negative, which was – USD 138,100 /y when the selling price of bioCNG CBM was at USD 5.535 /MMBtu and with MS as the most optimal purification option. This is due to a higher production cost than the selling profit. Table 1 listed down the cost breakdown of CBM off-site utilisation.

Table 1: Cost breakdown of CBM off-site utilisation.

Item	Unit	Value
Total Capex	USD	1,717,551
Annualized Capex	USD/y	137,820
Annual Opex	USD/y	299,001
Annual Sales	USD/y	298,722
Annual gross profit	USD/y	-138,100
Payback period	y	-

A sensitivity analysis was then carried out to explore the influence of product selling price on the annual profit of the system. The model output showed that the price would need to be at least USD 8.2 /MMBtu for this utilisation pathway to be feasible and with a payback period of 12 y. At a selling price of USD 12.9 /MMBtu, it can be more economically feasible than electricity generation and the payback period was found to be 4.32 y. Figure 3 shows the effect of CBM price on off-site pathway selection for a transportation distance of 100 km. Figure 4 shows the effect of compressed biomethane selling price with payback period. In addition to economic analysis, sensitivity analysis was also conducted on the impact of distance of pressure of system. The analysis was conducted for a range of distance from 10 km to 200 km for every 10 km. However, the optimal pressure identified was 200 bar regardless of distance.

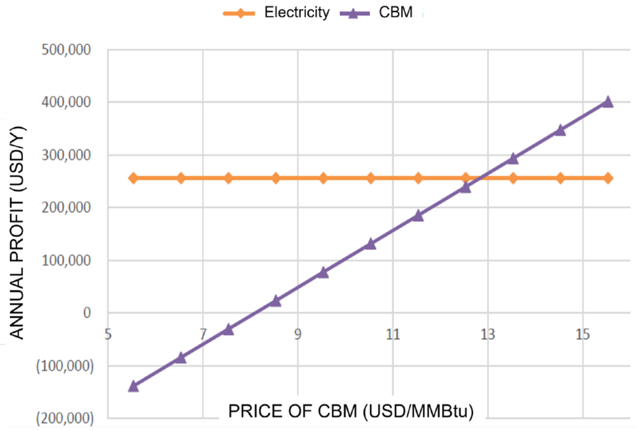

Figure 3: Effect of CBM price (USD/ MMBtu) for off-site product selection over 100 km transportation distance

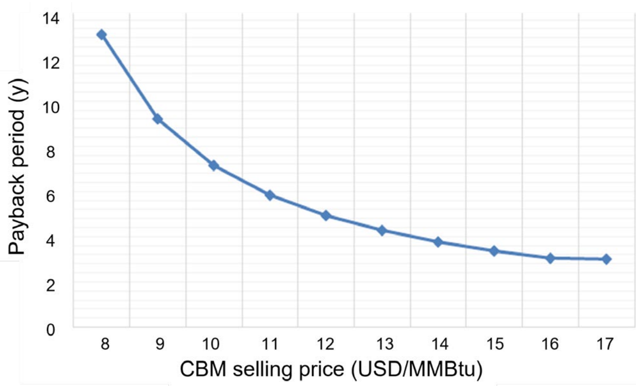

Figure 4: Payback period (y) based on different selling price for CBM (USD/MMBtu)

In order to ensure that CBM can be successfully implemented in Malaysia, a subsidy similar to that of Feed-in Tariff for power generation should be in place. Table 2 shows the subsidies required to ensure that the investment in CBM is profitable with acceptable payback period of 8 years, 5 years, and 3 years. It is recommended that at least a subsidy of 3.985 USD/MMBtu should be imposed for CBM off-site utilisation to ensure its economic viability.

Table 2: CBM subsidies requirement

Payback Period (y)	CBM Price (USD/MMBtu)	Subsidies (USD/MMBtu)
8	9.52	3.985
5	11.90	6.365
3	16.15	10.615

4. Conclusions

The study showed potential to optimise the supply-demand chain from AD of POME to offsite utilisation using a single optimisation model. The selected pathway consists of MS for purification, truck for transportation and electricity generation for off-site utilisation. The total investment cost was USD 2,934,564 with a payback period of 6 y. Sensitivity analysis showed that this period can be further shortened to 3 y if the feed-in-tariff rate was increased to USD 0.116/kWh. For off-site utilisation as CBM, a selling price of at least USD 8.2 /MMBtu is desirable. Future study can focus on the coupling use of spatial planning and optimisation to synthesise product allocation network for product transportation based on the energy demand of the locations.

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