Energy generation from palm oil mill effluent: A life cycle cost-benefit analysis and policy insights

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ABSTRACT

Malaysia's renewable energy policies do not cover production from waste, including the generation of biogas from palm oil mill effluent. This paper combines life cycle cost-benefit analysis (LCCBA) and the analytical hierarchy process (AHP) to provide new insights into costs and benefits of technologies over the life cycles, and on the basis of this information, asks experts to rank different options to enhance policy. The results show that the continuous stirred tank reactor has a higher LCC of 0.63 Million USD/year, compared to a LCC value of 0.55 Million USD/year for the covered lagoon bio-digester. In terms of cost-benefit, the continuous stirred tank reactor has a higher net present value of 0.46 Million USD/year, higher return on investment of 10.11% and a shorter payback period of 9.9 years compared to the covered lagoon bio-digester system, which has a net present value of 0.22 Million USD/year, return on investment of 7.79% and a payback period of 12.8 years. The continuous stirred tank reactor system therefore emerges as more economically feasible compared to the covered lagoon bio-digester system. On providing this information to experts using AHP, the three top ranked policy options emerged as: i) providing detailed environmental guidelines, ii) standardising technical guidelines for biogas installation and iii) covering the open pond wall using lining. Economic insights and policy opportunities based on this research can be used to inform policy decision making in multiple contexts where biogas plant projects are under consideration, in both Malaysia and globally.

Highlights

- Life cycle cost-benefit analysis (LCCBA) on palm oil mill effluent treatment
- Analytical hierarchy process (AHP) ranks policy options
- Combining LCCBA and AHP offers insights linking economic analysis & policy options

Keywords: Analytical hierarchy process, Biogas, Economic analysis, Multi criteria analysis, Policy, Renewable energy

Word count: 8,427 words

Abbreviations

POMs	Palm oil mills
POME	Palm oil mill effluent
CO_2	Carbon dioxide
LCCBA	Life cycle cost-benefit analysis
LCC	Life cycle cost
CBA	Cost-benefit analysis
CLB	Covered lagoon bio-digester
CSTR	Continuous stirred tank reactor
AHP	Analytical hierarchy process
LCA	Life cycle assessment
ROI	Return on investment
PP	Payback period
NPV	Net present value
IRR	Internal rate of return
USD	United States Dollar
EQA	Environmental Quality Act
DOE	Department of Environment
MPOB	Malaysian Palm Oil Board
MIDA	Malaysian Investment Development Authority
ITA	Investment tax allowance
FiT	Feed-in tariff
MW	Megawatt
JKR	Jabatan Kerja Raya
kWh	kilowatt-hour
C_i	Cost per unit electricity
t	Plant lifespan
r	Interest rate
EW_r	Earth works rate
D_r	Dumping rate

ACC	Annualised capital cost
AO	Annual operational cost
TCC	Total capital cost
AO	Annual operational cost
AI_i	Annual quantity of input (energy)
AM	Annual maintenance cost
AL	Annual labor cost
EC	Excavation cost
CS	Cost of site clearance
CCF	Cost of cut and fill
AOC	Area of cleared land (hectares)
VCL	Volume of cleared land (m^3)
AR	Annual revenues
A_o	Annual quantity of value-added product (energy)
P_o	Unit price
WACC	Weighted average cost of capital
A_{NNP}	Net annual profit after income tax
AD	Annual depreciation
d	Discount rate
A_P	Annual profit
IT	Annual income tax value
RS	Revenue from sales
TE	Total expenses
TI	Total investment
ACF	Annual cash flow
TNB	Tenaga Nasional Berhad
GMM	Geometric mean
CR	Consistency Ratio
CI	Consistency Index
$\boldsymbol{\lambda_{max}}$	Largest eigenvalue
RI	Random Index

P_j	Pairwise judgement
n	Number of elements
$\prod$	Product
a_{ij}	Preference of alternative ‘i’ over alternative ‘j’
GDP	Gross domestic product
ETSs	Emission trading systems
KETS	Korean ETS
PKS	Palm kernel shells

1. Introduction

Malaysia is rapidly developing towards a more industrial economy [1]. To power its development and economic growth, Malaysia relies on fossil fuels, which are expected to constitute >90% of the energy mix by 2040 [2]. Breakdown of the country's total primary energy supply in 2018 saw natural gas with the highest contribution (41.0%), followed by crude oil and petroleum products (29.5%), coal and coke (22.3%), hydropower (6.2%), biodiesel (0.4%), biomass (0.2%), solar (0.2%) and biogas (0.2%) [3]. To curtail its overreliance on fossil fuels, the Malaysian government set a target in 2018 of 20% renewable energy capacity in its energy mix by 2025 [4]. However, as renewable energy currently contributes only about 1-2% of the total energy mix [5], increased efforts are needed if Malaysia is to meet its target.

Malaysia has abundant biomass waste due to its suitable climate for agricultural activities, forestry, and timber industries, which typically generate a large amount of waste annually [6]. Utilising biomass waste for bioenergy production and other value-added products, such as furniture and composite for wood production, is commonly practised [6]. Approximately 16% of biomass waste is used for energy production in Malaysia, mainly from oil palm waste (51%) and wood waste (22%) [7]. Consequently, waste residue from oil palm could be used for co-generation and grid-connected biomass-based energy generation [7]. Residuals generated from palm oil mills (POMs) are mostly empty fruit bunches and palm oil mill effluent (POME) [8], both of which can be used to produce energy.

POME is commonly treated either via the use of an anaerobic pond or an open digester tank. These systems are implemented by 80% of Malaysia's POMs and emit substantial greenhouse gases into the atmosphere, mainly carbon dioxide (CO_2) and methane (CH_4) [9]. A more environmentally friendly alternative would be for POME to be treated in a biogas plant, but only 92 of the country's 454 POMs are currently equipped with one [10]. As biogas only contributes approximately 0.2% to the energy production mix [11], there is substantial untapped potential for biogas development in Malaysia. One way of harnessing it is by encouraging use of a closed anaerobic digestion system for converting POME into renewable biogas which can then be converted into electricity [9]. If all of the POME was to be anaerobically digested, Malaysia's 451 POMs could generate 68 million m^3 of POME, which has the ability to generate 500 MW of electricity [12]. However, lack of policy support from relevant authorities and government for the adoption of the required renewable energy technologies has resulted in slow growth in this area.

Lack of policy support is partly due to the absence of detailed information to guide policymakers on viable alternatives, especially with respect to the economics of POME treatment in the energy generation process. There is limited information, in particular, on the capital and operational costs for POME treatment technologies. This study addresses this gap, aiming to provide more comprehensive economic information and expert ranking of policy options to guide decision makers. This is achieved through two objectives: first, by undertaking a life cycle cost-benefit analysis (LCCBA), bringing together life cycle cost (LCC), while at the same time providing detailed costing calculation and cost-benefit analysis (CBA) for the covered lagoon bio-digester (CLB) and the continuous stirred tank reactor (CSTR) treatment technologies. Combining LCC and CBA is an approach that has been widely used by studies focussing on renewable energy. For instance, [13] used LCCBA for the economic assessment of palm oil-based biodiesel production in Indonesia in order to improve understanding of consequences and potential benefits from sterner policy implementation. Study by [14] used LCCBA to evaluate the economic assessment of bridge deck de-icing using a geothermal heat pump system as an economically viable and sustainable alternative. In other words, LCCBA is an effective method for assessing the anticipated costs and benefits of various alternatives, thereby aiding policymaking [15].

As a result, the present study also employs LCCBA, as it generates detailed costing information, which is crucial in developing an understanding of the on-ground situation in POMs, as well as for redefining the policy landscape, allowing incentives to be adjusted to better support investments in CLB and CSTR systems. These technologies were selected because these technologies are commercially available and used by the majority of the POMs with biogas facilities in Malaysia. However, high risks, such as investment costs and longer payback periods have reduced interest among stakeholders in providing the requisite finance [16]. This study includes detailed costings, thereby giving a broader picture of the economic feasibility of the POME treatment process in LCC compared to existing studies.

Second, policy options that are most appealing to the management staff of POMs were identified, thereby enabling recommendations for the development of a policy framework on the treatment of POME for energy generation. The analytical hierarchy process (AHP), a general theory of measurement which allows ranking of different options based on importance has been adopted [17]. Input data were presented to POM management staff during interviews, while surveys with a separate group of experts were carried out. Coupling information on costs with data from the AHP allowed for a more holistic understanding of the prerequisites for enhancing investment and innovation processes in biogas generation from POME.

2. Background

The environmental impacts of the two different POME treatment technologies, the CLB and the CSTR, using LCA, were quantified by [18]. The findings showed that global warming potential, eutrophication potential and acidification potential were the most significant environmental impacts resulting from POME treatment for energy generation for both systems. LCA showed that while both the CLB and CSTR systems result in a net environmental benefit by lowering global warming potential and acidification potential, the systems increase the potential for eutrophication. Nevertheless, the eutrophication potential can be lowered by measures such as increasing the usage of POME anaerobic sludge for composting and covering the open pond wall with a lining [18]. While these insights using LCA are useful, the study did not provide insights into the economic costs and benefits of the CLB and CSTR.

Economic investigations have nevertheless taken place previously. A first strand of studies focusses on one type of biogas technology, either the CLB or the digester tank system for the treatment of POME for energy generation. A study by [19] was based on a LCCBA of electricity generation from bio methanation of POME treatment and land application of digester effluent in Malaysia. Different reactor temperatures of 45ºC, 50ºC and 55ºC were compared, while the economic aspects considered were the annual return on investment (ROI) and payback period (PP). The most economically feasible option was the one with a reactor temperature of 55ºC, with the highest ROI of 58% and lowest PP of 1.5 years. Capital costs did not cover the costs for POME pre-treatment. Estimations of costs in terms of CBA were reported by [20] and [21]. The former study [20] reported the benefits from implementing a carbon emission reduction scheme by evaluating the net present value (NPV), internal rate of return (IRR) and PP of using biogas for four different purposes: boilers, electricity generation, flaring and cooking gas. However, no detailed breakdown of investment and operational costs was shown. The latter study [21], compared six different biorefinery alternatives in Colombia, including production of biogas from

POME. Economic benefits from the compared alternatives came from electricity generation. With respect to the biogas generation alternative, NPV was 2.5 Million USD, IRR 24% and a PP of 6 years. However, no detailed breakdown of capital costs was reported in this study, meaning it was not possible to compare across the two options.

A second strand of studies compares the CLB and digester tank system in order to provide evidence on the economic aspects of utilising biogas from POME treatment for on-grid electricity in Malaysia (see [22], as well as [23,9]). However, these studies focused only on CBA, providing no detailed breakdown of capital and operational costs for each system. For instance, [22] showed that the PP of the CLB was 6.2 years, while the digester tank system had a PP of 8.3 years. Also, the IRR values were compared, showing that the CLB yielded a value of 16.1%, whereas the digester tank gave a value of 12.1%. This showed the CLB to be more economically feasible than the digester tank system. However, as noted, no detailed information was provided on capital and operational costs for both CLB and digester tank for the treatment of POME for energy generation. This gap is addressed by the present study, as it provides detailed information on costs for each system. Such details are imperative to better reflect the on-ground situation, as well as facilitate the development of a policy framework for Malaysia. Combining LCC and CBA in an economic assessment enables a more holistic understanding of costs and benefits for each system and provides detailed breakdown of capital and operational costs for both systems.

Having detailed costing data for both technologies using LCCBA is crucial for POM managers. However, such information alone is not enough. For POMs to confidently invest in biogas technologies, POMs also need to be supported by a favourable policy environment. Coupling, information on costing data with an understanding of what POM managers perceive a favourable policy environment can facilitate investments in the generation of biogas from POME. To better understand this, the AHP method was employed. AHP is a system of ranking different options against each other based on importance. In the present study, POMs with a biogas plant in the state of Johor, Malaysia were identified, and managers, engineers, and executives were interviewed to examine the interviewees' views on the specific policies and measures the Malaysian government should adopt in order to facilitate investment in biogas generation from POME.

The main overarching environmental legislation currently in place in Malaysia is the Environmental Quality Act (EQA) 1974, which was introduced by the Department of Environment

(DOE). The primary purpose of the EQA is the prevention, abatement, and control of pollution, and the enhancement of the environment in Malaysia. Regarding the allowable level of discharge of biological oxygen demand from crude palm oil specifically, this has been set at 100 mg/L [24]. Also, effective from 1 January 2014, the Malaysian Palm Oil Board (MPOB) made it compulsory for all existing and upcoming POMs involved in the processing of oil palm to install methane-capturing facilities or emission avoidance measures [25]. The only guidelines that currently exist on setting up biogas facilities in POMs focus on the installation of anaerobic digesters and safety measures for the treatment of POME for energy generation. As for existing pond systems, there are no regulations that cover the pond wall.

To promote environmental conservation and resource management, the Malaysian Investment Development Authority (MIDA) provides an investment tax allowance (ITA) for the purchase of green technology equipment/assets. The ITA is an allowance of 100% on qualifying capital expenditure (plant, equipment, factory, machinery used for approved projects), which can be offset against 70% of statutory income up to 2020. An ITA has to be fully utilised by carrying forward any unutilised allowance into the following year [26]. However, the major drawback of the ITA is the complicated application procedure, which involves gaining approval from both the MIDA and GreenTech before an ITA can be awarded. Such drawbacks mean that relevant groups fail to make use of the ITA as an initiative to encourage the implementation of green technology in Malaysia.

Another method for promoting the use of green technology and renewable energy in Malaysia is the feed-in tariff (FiT). This mechanism obliges energy utilities to buy renewable energy from producers at a mandated price. According to the Renewable Energy Act of 2011, the tariffs for particular technologies differ according to the capacity (< 4 MW, 4-10 MW, 10-30 MW) of the electricity generating facilities. An extra bonus is given to facilities if locally manufactured or assembled technology is used, and if the facilities achieve high efficiency in electricity generation [27]. Regarding the efficacy of the Renewable Energy Act 2011, [28] concluded that it depends on the effectiveness of FiT implementation. However, FiT was found to be an unsustainable mechanism to support long-term renewable energy growth due to stiff competition between renewable energy technologies [29] and because each technology may require a different FiT mechanism [30] to benefit the country and public. The current FiT mechanism indirectly imposes a heavy burden on the public when electricity costs rise [28]. [28] concluded that the FiT is still considered effective in establishing a renewable energy market in the country, as FiT implementation supports small-scale renewable energy generation. Nevertheless, future amendments to the Renewable Energy Act 2011 are needed [28]. Information from the present study could inform such amendments.

3. Methods

3.1. Life cycle cost-benefit analysis (LCCBA)

3.1.1. Goal and scope of the study

The goal of this study was to estimate the LCCBA for the two selected technologies for energy generation. For an overview of the two POME treatment technologies see Fig. A.1 and Fig. A.2 in the supplementary material. The study was carried out in two POMs in Malaysia, from gate to gate, including POME transfer from the POM, pre-treatment of POME, biogas generation in an anaerobic digester, purification of biogas, utilisation of gas engine to combust biogas for energy generation, and post-treatment of digestate POME before being directed for land application, with the electricity generated being transmitted to the national grid. Transmission of electricity to the grid was credited for the revenue from the sales of the recovered energy resources[1]. All costing information was obtained directly from the POMs, except for the excavation costs of the ponding system, which was calculated based on values obtained from [31,32].

The functional unit for the POME treatment was defined as the treatment of POME for 1 kWh of electricity generation. The lifetime of the POME treatment plant was assumed to be 20 years for both POMs, based on information obtained from the representatives of the mills. Lifetime refers to the plant lifespan.

[1] There is no plug flow along with CSTR system in this study.

3.1.2. Economic analysis

The method outlined here was used to evaluate the economic feasibility of two different POME treatment technologies for energy generation considering the LCC, NPV, ROI and PP for each option. The data used, and calculations made, are explained below.

3.1.2.1. Life cycle costing (LCC)

LCC can evaluate the economic performance of products comparing costs over a specified period of time, considering all related economic factors, in terms of future operational costs and initial costs. ISO 15686 suggests a framework consisting of four steps: (1) alternative strategies should be defined for evaluation; (2) economic criteria should be identified; (3) obtain and accumulate significant costs; (4) execute risk assessment (sensitivity analysis) [33]. LCC is in line with the life cycle method of assessing a product, covering one or more actors in the product life cycle, and including externalities that are targeted in future decision making [34]. The process considers acquisition costs, operation costs, maintenance and repair costs, and disposal costs [35], as well as externalities. However, in this study, externalities have been excluded due to insufficient information.

Table 1 summarises the costs involved in the economic calculation covering included and excluded cost items for LCC. Since the elements involved in the LCC calculation were based on annual costings, the total capital cost of each system was annualised, assuming a 20-year lifespan and 3.64% average interest rate for the year 2020 (Jan-Sept), in Malaysia [36]. Most of the cost values were obtained directly from the two-case study POMs. Excavation costs were calculated using the guidelines by [31] and [32]. Input data for the LCC are listed in Table 2.

Table 1 Costs involved for economic calculation

Equation no.	Type of cost	Inclusion	Exclusion	Reference
1	LCC	• Acquisition (annualised capital costs) • Operation costs, maintenance and repair (annual operational costs)	-	[13]
2	Annualised capital cost	• Excavation costs for the ponding system (pre- and post-treatment of POME) • Anaerobic digesters (CLB and CSTR systems) • Facilities for the purification of biogas • Energy generation by combusting the biogas • Transmitting the electricity generated to the grid	• Costs of land and disposal	[13]
3-5	Excavation costs (annualised capital cost)	• Excavation cost for ponding system • Costs involved for the CLB and CSTR systems consist of site clearance, cut and fill and dumping the soil cleared	• -	[31,32]
6	Annual operational costs	• Annual quantity of energy • Annual maintenance cost • Annual labor cost	-	[13]

Table 2 Values for symbol used in LCC calculation

Item	Symbol	Range of electricity	Value	Reference
Biogas plant				
Electricity	C_i	First 200 kWh 201 kWh onwards	USD 0.092/kWh USD 0.11/kWh	[37]
Assumptions				
Plant lifespan	t		20 years	Obtained from the mill
Interest rate	r		3.64%	[36]
Earth works rate	EW_r		USD 778.90	[32]
Dumping rate	D_r		USD 1.68	[31]

Current exchange rate 1 USD = 4.12 Malaysian Ringgit (local currency)

$$\mathrm{LCC} = \mathrm{ACC} + \mathrm{AO} \tag{1}$$

where:
LCC is life cycle cost (annual cost)
ACC is annualised capital cost
AO is annual operational cost

$$\mathrm{ACC} = [\mathrm{r}/(1 - (1 + \mathrm{r})\exp(-\mathrm{t}))] \times \mathrm{TCC} \tag{2}$$

where:
ACC is annualised capital cost
r is interest rate
TCC is total capital cost
t is the plant lifespan

Assumptions made for the calculation of the excavation cost are that: i) the land area has a flat surface and is at a same level, ii) site clearance is to cut down the existing trees, iii) only cut and fill processes are involved, iv) no concreting is involved as only earth materials have been used and v) that dumping is carried out within a 1 km radius of the site. The excavation cost is part of the LCC, coming under the annualised capital cost. The excavation cost is the summation of on-site clearance costs and cut and fill costs, as follows:

$$\mathrm{EC} = \mathrm{CS} + \mathrm{CCF} \tag{3}$$

where:
EC is excavation cost
CS is cost of site clearance
CCF is cost of cut and fill

$$\mathrm{CS} = \mathrm{EW_r} \times \mathrm{AOC} \tag{4}$$

where:
CS is cost of site clearance
EW_r is earth works rate
AOC is area of cleared land (hectares)

$$\mathrm{CCF} = \mathrm{D_r} \times \mathrm{VCL} \tag{5}$$

where:
CCF is cost of cut and fill
D_r is dumping rate
VCL is volume of cleared land (m^3)

$$\mathrm{AO} = \sum(\mathrm{AI_i} \times \mathrm{C_i}) + \mathrm{AM} + \mathrm{AL} \tag{6}$$

where:
AO is annual operational cost
AI_i is annual quantity of input (energy)

C_i is cost per unit electricity
AM is annual maintenance cost
AL is annual labor cost

3.1.3.2. Revenues

Revenues (Eq. 7) present the multiplication of annual quantity of value-added product multiplied by unit prices.

$$AR = A_o \times P_o \quad (7)$$

where:
AR is annual revenues
A_o is annual quantity of value-added product (energy)
P_o is unit price

3.1.2.2. Cost-benefit analysis (CBA)

CBA can be employed to estimate the total costs and benefits of an activity or a project [38]. In contrast, LCC does not include benefits [39]. LCA and LCC focus on the life cycles of the evaluated products, while CBA considers the lifetime of a particular project, making the lifetime of used products secondary [40]. Utilising both LCC and CBA makes the economic evaluation more complete. The overall costs and benefits of a project offer important insights for policy and decision makers [14]. Thus, LCCBA is a viable and strong method to assess the anticipated costs and benefits of various alternatives, and help in making final decisions [15]. Additional economic factors under CBA, such as ROI, PP and NPV, are necessary to evaluate the desirability and feasibility of a system [41]. NPV (Eqs. (8-11)) is the overall financial status of a project. "Invest if the NPV of investing exceeds zero" is a popular motto among managers [42]. From an NPV perspective, it is crucial to evaluate the eligibility of investments over their lifetime [43]. NPV is calculated based on the discounted income and costs [13]. The discount rate, or weighted average cost of capital (WACC), was set at 6%, based on [44]. The current income tax rate value is assumed to be 24% based on [45]. ROI is an annual interest rate from the profits on the capital investment [46]. Also, it is used to measure profitability. ROI is calculated using Eq. 12. PP (Eqs. (13-14)) refers to the period of time required for the capital investment to equal the annual profits. PP is also known as the cash recovery period, payoff period, payout period or payout time, and is used to compare alternatives in early evaluations [47].

$$NPV = \sum_{1}^{n} \left[(A_{NNP} + AD)/((1 + d)\exp 1)\right] \tag{8}$$

where:
NPV is net present value
A_{NNP} is net annual profit after income tax
AD is annual depreciation
d is discount rate

$$A_{NNP} = A_P - (A_P \times IT) \tag{9}$$

where:
A_{NNP} is net annual profit after income tax
A_P is the annual profit
IT is the annual income tax value

$$A_P = RS - TE \tag{10}$$

where:
A_P is the annual profit
RS is the revenue from sales
TE is the total expenses

The annual depreciation cost is calculated using the total capital cost divided by the plant lifespan, particularly referring to the machines' lifespan using Eq. 11, adapted from [13].

$$\mathrm{AD} = \mathrm{TCC}/\mathrm{t} \tag{11}$$

where:

AD is annual depreciation

TCC is total capital cost

t is plant lifespan

$$\mathrm{ROI} = [(\mathrm{A_{NNP}} + \mathrm{AD})/\ \mathrm{TI}] \times 100\% \tag{12}$$

where:

ROI is return on investment

A_{NNP} is net annual profit after income tax

AD is annual depreciation

TI is total investment

$$\mathrm{PP} = \mathrm{TI}/\mathrm{ACF} \tag{13}$$

where:

PP is payback period

TI is total investment

ACF is annual cash flow

$$\mathrm{ACF} = \mathrm{A_{NNP}} + \mathrm{AD} \tag{14}$$

where:

ACF is annual cash flow

A_{NNP} is net annual profit after income tax

AD is annual depreciation

3.1.3. Sensitivity analysis

Sensitivity analysis looks into alternative ways to improve the economic feasibility of a process by addressing uncertainties in relation to market fluctuations and investment. Sensitivity tests can be carried out by manipulating the key assumptions in relation to the variation in economic performance. Some studies related to palm oil undertook a sensitivity analysis based on operation and maintenance cost, capital cost, interest rate and raw material prices [47,48]. A sensitivity test for this study was conducted based on the variations in net annual profit, as shown in Table 3.

Table 3 Sensitivity analysis parameters

Indicator	Parameter	Base value (USD/kWh)	Variations to the base value
Annual profit (Million USD/year)	FiT rate	0.078	+5%, +10%, +15% +20%, +25%, +30%

Current exchange rate 1 USD = 4.12 Malaysian Ringgit (local currency)

3.2. The analytical hierarchy process (AHP)

3.2.1. Interviews

The second objective involved employing the AHP method to identify and rank possible policy options that in the opinion of POM management staff could create an enabling policy environment for investing in the two technologies examined by this study. To conduct interviews, POMs with a biogas plant in the state of Johor, Malaysia were selected. POMs were chosen based on the criterion that the POMs had either electricity-generating or non-electricity generating facilities. Eighteen POMs fulfilled the requirement, but access relied on securing internal recommendations by the high-level management within each one. This proved possible for eight POMs. All eight POMs were approached, but despite follow-up invitations, only five responded and were therefore sampled. Interviewees were contacted by phone and email and comprised managers, engineers and executives directly involved in monitoring the biogas plant in the respective mills.

Interviews were conducted with eleven members of POM management across five POMs (Table 4).

Table 4 Number of interviewees from participating POMs

POM	Number of interviewees	Position
A	3	Assistant mill manager, Supervisor (biogas plant), Executive chargeman
B	2	Senior engineer, Assistant general manager
C	2	Assistant engineer, Senior assistant engineer
D	2	Senior mill assistant engineer, Executive
E	2	Assistant engineers

Two of the sampled POMs generate biogas for energy, one using the CLB and the other using the CSTR system, and both sell the electricity generated to the grid. One of the other three remaining POMs has chosen to use the closed tank system for electricity generation for its own plant consumption, while the other two POMs use biogas as fuel for boilers, but not for energy generation. Following presentation of the LCA findings emerging from [18] and LCCBA, interviewees were invited to suggest possible policy solutions under four main criteria: i) environmental impact, ii) investment cost, iii) operational cost and iv) revenue, drawing on the interviewees own knowledge and experience. The interview outputs (solutions) listed in Table 5 were then used as the inputs for the AHP.

Table 5 Description of the main criteria (environmental impact, investment cost, operational cost and revenue) and possible solutions

Main criterion (description)	Possible solutions	Description
Environmental impact (potential impacts due to gaseous emissions or various accumulations of nutrients in the environment)	Cover open pond wall using lining	The open pond wall should be covered to avoid any leaching and pollution of groundwater.
	Do not cover open pond wall	The open pond wall should not be covered.
	Provide detailed environmental guidelines	The current environmental regulation needs to be revised to provide a detailed description of the environmental guidelines to be followed by the millers.
Investment cost (total capital cost involved in setting up a biogas treatment facility)	Provide subsidy for transmission of electricity to the grid	The Malaysian Government could provide a full or partial subsidy for the transmission of electricity to the grid.
	Provide subsidy to set up biogas facilities	No subsidy is currently provided specifically to set up the biogas facilities.
	Implement an easy application procedure for the ITA	The complexity of the ITA application procedure delay the move towards implementing green technologies.
	Enable private millers to supply waste to a centralised POME waste treatment facility	Private millers could supply their generated waste to a centralised POME waste treatment facility for further treatment if good infrastructure and necessary logistical setups are in place to facilitate delivery of waste to the facility.

Operational cost (total utilities cost, maintenance cost and labor cost)	Standardise technical guidelines for biogas installation	The MPOB and Tenaga Nasional Berhad (TNB) could cooperate and come up with standardised technical guidelines for the installation of biogas facilities.
	Give investors freedom to purchase either locally or imported manufactured technology	Investors should have the freedom to decide on the type of technology or equipment to be installed according to their preference.
Revenue (profit obtained through the sales of electricity to the grid)	Set high, fixed FiT rate	A lower FiT is not attractive to investors.
	Allow variation in FiT rate	The FiT rate should increase annually to ensure that the revenue obtained is sufficient to run the plant for a longer period of time.
	Set FiT rate according to electricity transmission distance to grid	The FiT rate should increase in line with the electricity transmission distance to the grid.
	Introduce new legislation on carbon trading	Currently, no credits are provided for carbon emission reductions, which makes green technology look unattractive to investors. Carbon trading could be introduced by the Malaysian Government as an incentive to stimulate adoption of green technologies.

3.2.2. Analytical hierarchy process (AHP)

AHP is one of the most commonly used quantitative methods for multi-criteria decision making [49]. AHP is useful when it comes to obtaining a single assessment value based on different criteria or indicators. The AHP method described by [17] has four steps:

1) Defining the problem and then forming a hierarchy with the aim at the first level;
2) Formulation of pairwise comparison questionnaires or surveys for experts or stakeholders to provide experts' point of view based on a nine-point scale [17];
3) Construction of a pairwise comparison matrix with respect to possible solutions under each main criterion, drawing on the survey data obtained under step 2.

Geometric mean (GMM) is used to obtain consensus in the pairwise judgement when more than one respondent is involved [50]. By using the GMM method (see Eq. 15), a set of eigenvectors that serve as local priorities in a complete square matrix is developed. The priorities present the relative importance of the elements within its range of category and on the element in the level above its range [17]. The relative impact of the elements on the level above and within its category are represented by the priorities. The "normalise result" column shown in Fig. 1 multiplied by 100% refers to the "priority weight (%) in Tables (8-12)". No assumptions were made to perform the calculation. However, through this method, each expert involved in the survey was able to choose their preferred and prioritised option which led to the AHP analysis. Tables (8-12) provide the aggregate of these prioritisations.

4) The degree of randomness in the judgements used to develop the matrix is measured [51]. The Consistency Ratio (CR) used to measure the consistency of answers given by the respondents in the questionnaire is a tool suggested by [52]. The CR is calculated using Eq. 16 [53] notes that CR has to be less than the value of 0.1 to be acceptable. The Consistency Index (CI) is determined through calculating the difference of the largest eigenvalue (λ_{max}) to the number of attributes (n) in each category, as shown in Eq. 17. The Random Index is the CI measured for each matrix of size n with random matrices [17].

$$P_j = \sqrt[n]{\prod_{i=1}^{n} a_{ij}} \tag{15}$$

where:

P_j: Pairwise judgement

n : number of elements

$\prod$: Product

a_{ij}: preference of alternative 'i' over alternative 'j'

	The matrix				Eigenvector		Normalise Result
	A1	A2	A3	A4			
A1	$\frac{w1}{w1}$	$\frac{w1}{w2}$	$\frac{w1}{w3}$	$\frac{w1}{w4}$	$\sqrt[4]{\frac{w1}{w1}\times\frac{w1}{w2}\times\frac{w1}{w3}\times\frac{w1}{w4}}$	= a	$a/_{Total} = \text{x1}$
A2	$\frac{w2}{w1}$	$\frac{w2}{w2}$	$\frac{w2}{w3}$	$\frac{w2}{w4}$	$\sqrt[4]{\frac{w2}{w1}\times\frac{w2}{w2}\times\frac{w2}{w3}\times\frac{w2}{w4}}$	= b	$b/_{Total} = \text{x2}$
A3	$\frac{w3}{w1}$	$\frac{w3}{w2}$	$\frac{w3}{w3}$	$\frac{w3}{w4}$	$\sqrt[4]{\frac{w3}{w1}\times\frac{w3}{w2}\times\frac{w3}{w3}\times\frac{w3}{w4}}$	= c	$c/_{Total} = \text{x3}$
A4	$\frac{w4}{w1}$	$\frac{w4}{w2}$	$\frac{w4}{w3}$	$\frac{w4}{w4}$	$\sqrt[4]{\frac{w4}{w1}\times\frac{w4}{w2}\times\frac{w4}{w3}\times\frac{w4}{w4}}$	= d	$d/_{Total} = \text{x4}$
						Total	

Fig. 1. Framework of GMM calculation

$$CR = CI/RI \tag{16}$$

where:

CR: Consistency Ratio

CI: Consistency Index

RI: Random Index

$$CI = (\lambda_{max} - n)/(n-1) \tag{17}$$

where:

λ_{max}: largest eigenvalue

n : number of elements

The present study followed these four steps. The literature remains undecided as to how many respondents are needed to justify the reliability of the results obtained from AHP, ranges from one to a large number of respondents [54]. In this study, seven experts participated from energy and environment (4 respondents), renewable energy (2 respondents), and market operations (1 respondent). All experts had five years' minimum working experience in an energy or environmental or related department or agency that deals with the palm oil industry, provision of incentives and energy generation. Surveys were conducted through direct meetings. Overall weights and ranking of possible solutions were calculated by multiplying the weight of each possible solution by the priority weight of the main criterion. The small number of respondents was one of the limitations of this study as it was difficult to engage with all relevant stakeholders due to slow responses and a lack of replies.

4. Results

4.1. LCCBA

4.1.1. Cost for setting up two types of POME treatment technologies for energy generation

Table 6 lists the capital costs for the implementation of the two different biogas technologies in the two POMs in Malaysia. Investments are needed for both treatment technologies. The capital costs of the CSTR system are much higher than for the CLB system, due to the utilisation of a greater number of steel tanks compared to the ponding system, which only requires excavation and landfilling costs. While the CLB system is much cheaper, it still requires a larger area of land, which includes the land cost to build the system [55], while the CSTR system does not consume much space. However, both technologies are efficient in terms of capturing biogas and thus have environmental benefits.

Annual costs and revenues for both systems are listed in Table 7. Since the feedstock is the POME waste from palm oil production, there is no cost in terms of inputs of raw materials. This is already considered the biggest saving for the implementation of the biogas facilities. Factors that affect the total cost in the range of 50-80% would be the feedstock, according to previous studies [35,47,48,56]. Moreover, there is no chemical or catalyst added to the POME waste for the production of biogas based on the information obtained directly from both POMs. Annual capital and operational costs for both systems were obtained directly from the mill representatives. Lack of data availability on the annual operational costs of the

CSTR system led to assumption of costs amounting to 5% of the total capital cost, in line with findings from [20]. Comparison between the CLB and CSTR shows the CLB has the higher annual operational cost. However, the result is still reliable. The representative from POM 2 mentioned that the electricity supply for the utilities is coming from the POM's own gas engine. POM 2 has two gas engines, where one engine supplies electricity to the grid, while the other supplies electricity for the mill to use. Thus, there is no need to purchase electricity from the grid unless the engine is under maintenance.

Currently, revenues for both POMs come from the sales of electricity to the grid. The electricity generated and supplied to the national grid by both POMs is 1 MWh. The CSTR system obtains higher revenues compared to the CLB system due to its generation of more electricity, as the operating hours are greater for POM 2 (8,760 hours) compared to POM 1 (7,200 hours). Besides, POM 2 receives USD 0.0049/kWh, a higher FiT compared to POM 1. The FiT mechanism requires energy utilities to buy renewable energy from producers, at a mandated price. This ensures that renewable energy is a long-term investment for industries, companies and even for individuals, by setting a favourable price per unit of power and guaranteeing access to the grid. The FiT provided to a particular technology varies based on the facilities' capacity according to the Renewable Energy Act 2011. Additional bonuses are given for employing local technology and achieving high efficiency in electricity generation [27].

Table 6 Capital cost of CLB and CSTR systems

Equipment	CLB (Million USD)	CSTR (Million USD)
Ponding system (pre- and post-treatment of POME)	0.24	0.12
Biodigester (CLB) including blowers and diffusers	0.87	-
Biodigester (CSTR) and storage tank	-	1.14
Overflow tank	-	0.24
Tanks (de-oiling tank, screening tank, raw POME tank, distribution tank)	-	0.39
Piping system (POME and biogas)	0.21	0.05
Biogas purification and electricity generation systems (booster fan- for CSTR, scrubber, chiller, engine room and gas engines)	1.14	2.44
Pumps and motors	0.012	0.07
Electricity transmission to grid	0.56	0.41
Total	**3.03**	**4.86**

Current exchange rate 1 USD = 4.12 Malaysian Ringgit (local currency)

Table 7 Costs and revenue of CLB and CSTR systems

Items	Unit Price (USD/kWh)	CLB (Million USD/year)	CSTR (Million USD/year)
Annual operational costs			
Utilities cost (electricity)	0.092	0.00018	0.24
	0.11	0.032	
Labor cost		0.077	
Maintenance cost		0.20	
Annualised capital cost		**0.22**	**0.35**
LCC		**0.53**	**0.59**
Annual depreciation cost		0.17	0.24
Revenue			
Electricity to grid	0.078 (CLB) 0.10 (CSTR)	0.57	0.89
Annual profit		**0.57**	**0.89**

Current exchange rate 1 USD = 4.12 Malaysian Ringgit (local currency)

4.1.2. Results of the economic analysis

The NPV, ROI and PP of the CLB and CSTR systems are shown in Fig. 2. The CSTR system has the highest NPV of 0.54 Million USD/year, highest ROI of 11.73% and shortest PP of 8.5 years, compared to the CLB system with NPV of 0.22 Million USD/year, ROI of 7.79% and PP of 12.6 years. The CSTR system seems to be most economically feasible. Previous studies [22,23,9] have performed estimated cost-benefit calculations comparing the lagoon (CLB) and tank system. All three studies reported that for on-grid electricity generation, a digester tank has a PP of 8.3 years while the CLB system has a PP of 6.2 years without any additional bonuses provided. Additional bonuses are only given for the use of gas engine technology with an electrical efficiency of >40% and the use of locally manufactured and assembled gas engine technology [57]. In the present study, the CSTR system has a PP of 8.5 years which is slightly higher compared to the previous studies due to the difference in total capital cost and operational cost. The CLB system has a PP of 12.6 years which is double the PP from the previous studies and greater than the CSTR system, even though the total capital cost of the CLB is lower than that of the CSTR. The main reason for the longer PP could be the lower FiT rate provided for the electricity sold to the grid by POM 1, and the higher operational cost. The higher operational cost for the CLB is due to high maintenance requirements (i.e., of gas engines), which were purchased overseas according to representatives of POM 1.

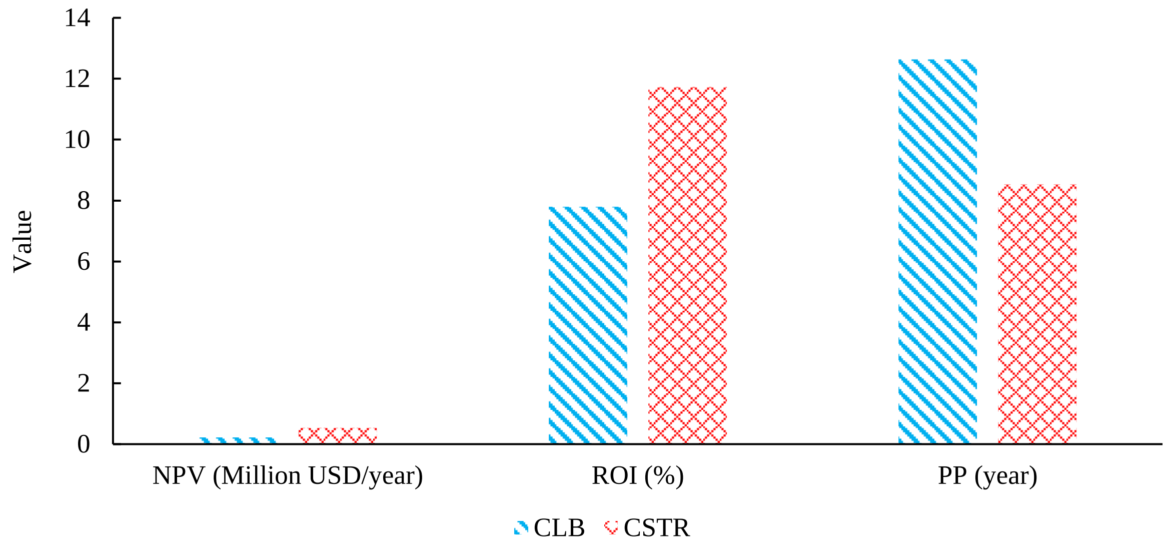

Fig. 2. NPV, ROI and PP of the CLB and CSTR systems

The FiT rate therefore plays an important role in ensuring the profitability and feasibility of the POME treatment process as it is the only revenue obtained by both the POMs. A sensitivity analysis varying the FiT rate was carried out to improve understanding of the economic feasibility of the CLB system in particular.

4.1.3. Sensitivity analysis: Effects of change in rate of FiT

The sensitivity analysis was carried out for the CLB system, so as to improve its economic feasibility. Since POME treatment to energy generation is not the major source of income for the POM, as long as there is a positive NPV, a higher ROI and PP of less than 10 years, the system is more economically feasible. A sensitivity analysis was carried out for the CLB system, varying the rate of FiT, as the rate provided for the CLB is much lower compared to the CSTR system. Sensitivity analysis was not conducted for the variations in different cost items. This is because [14], who studied palm oil biodiesel production in Indonesia performed a sensitivity analysis for parameters that can impact net income, including fresh fruit bunch cost, electricity price from biomass, biofertiliser price and biodiesel price. However, only the sale price of biodiesel and feedstock (fresh fruit bunch) cost affected the net income [14]. In contrast, in the present study, the feedstock is POME which is a waste material, while the output is the electricity sold to the grid. Given the variation in FiT rate affects the price of the electricity sold to the grid, the sensitivity analysis focuses on the variations in FiT rate. Fig. 3 shows the sensitivity analysis findings, comparing the variations in NPV, ROI and PP based on the FiT rate base values listed in Table 2.

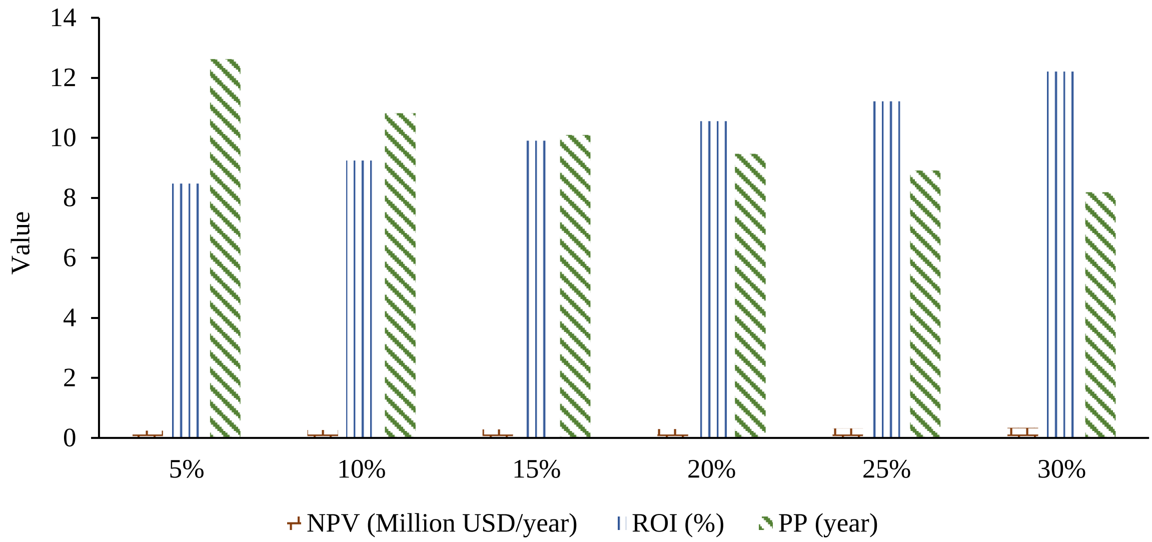

Fig. 3. Sensitivity analysis on annual profit (Million USD/year) of CLB system with parameter change of +5%, +10%, +15%, +20%, +25% and +30% from the base value on rate of FiT. The 5% variations in FiT rate followed [58] who aimed to identify the optimal system configuration and cost-effective design of a grid connected rooftop photovoltaic under FiT or net metering mechanisms in Poland. There is no standard method to perform sensitivity analysis based on the ISO standards [59], so, the scenario undertaken in this study was assumed to illustrate possible alternative improvement.

As the FiT rate increases by every 5%, NPV value increases, ROI increases, while the PP value reduces. When the FiT rate is 20% higher than the base value (USD 0.078/kWh), the NPV and ROI value increase to 0.30 Million USD/year and 10.56%, respectively, while the PP value reduces to 9.5 years. The highest NPV and ROI value of 0.34 Million USD/year and 12.21%, respectively and the lowest PP value of 8.2 years is considered to be the best solution when the FiT rate is at 30%. A 16% increment to the base FiT value would be the minimum needed to achieve minimum economic feasibility, while a 30% increment on the base value would result in a FiT rate of USD 0.10/kWh; similar to the rate for the CSTR. To enable the

CLB system to be more attractive to investors, electricity buyers could increase the FiT rate given to POMs employing the CLB system.

4.2. Criteria hierarchy results

4.2.1. Main criteria hierarchy results

Table 8 shows the ranking of the main criteria for policy consideration, showing 'environmental impact' (45.93%) is most highly prioritised, followed by 'investment cost' (20.69%), 'operational cost' (19.51%), and 'revenues' (13.87%). This clearly demonstrates that environmental aspects were given more importance compared to the economic aspects, which is in line with Malaysia's target under the Paris Agreement of reducing greenhouse gas emissions intensity of gross domestic product (GDP) by 45% by 2030 relative to the emissions intensity of GDP in 2005 [60].

Table 8 Main criteria rankings for policy consideration linked to POME treatment for energy generation

Main criteria	**Priority Weight (%)**	**Rank**
Environmental impact	45.93	1
Investment cost	20.69	2
Operational cost	19.51	3
Revenues	13.87	4

4.2.2. Results of possible solutions within main criteria

The 'environmental impact' main criterion results are shown in Table 9. The ranking is not surprising, as all eleven interviewees mentioned that the existing environmental regulation guidelines for the treatment of POME for energy generation are too general and insufficiently specific. This suggests that POM managers do not have a clear understanding regarding issues like how to ensure the allowable emission limit is achieved or the proper way to construct a ponding system to avoid leaching/overflows.

Table 9 Possible solution rankings targeting environmental impact

Possible solutions	Priority Weight (%)	Rank
Cover open pond wall using lining	26.24	2
Do not cover open pond wall	8.30	3
Provide detailed environmental guidelines	65.46	1

Consistency Ratio (CR) = 0.0816

For the 'investment cost' main criterion (see Table 10), the recommendation of 'enabling private millers to supply waste to a centralised POME waste treatment facility' (41.26%) was ranked highest. This option is important as it would not be an easy task to encourage private millers to implement biogas facilities due to the high investment cost required, especially as some of the private millers are small-scale waste producers. To address this, the POME waste generated by private millers could be supplied to a centralised POME treatment facility for further treatment for biogas generation and could also be converted into value-added products. Through this, the cost burden of installing expensive biogas facilities faced by the private millers could be reduced, making the establishment of a centralised POME treatment facility, which could count on having a continuous supply of POME waste for biogas generation, a reliable proposition.

Table 10 Possible solution rankings targeting investment cost

Possible solutions	Priority Weight (%)	Rank
Provide subsidy for the transmission of electricity to grid	16.90	3
Provide subsidy to set up biogas facilities	10.28	4
Implement easy application procedure for ITA	31.55	2
Enable private millers to supply waste to a centralised POME waste treatment facility	41.26	1

Consistency Ratio (CR) = 0.06994

As can be seen in Table 11, 'standardising technical guidelines for biogas installation' (71.97%) was the highest priority amongst the possible solutions targeting operational cost, followed by 'giving investors freedom to purchase either locally or imported manufactured technology' (28.03%). The purpose of the technical guidelines would be to ensure that every

POM followed a clear set of standards, preventing miscommunication. This would ensure the operational cost of biogas facilities is manageable and that the companies involved would generate sufficient profits to sustain the biogas plant. One out of the eleven interviewees mentioned that regulations such as those on using only imported technology (e.g., gas engines) could be used as a condition to enable TNB to purchase electricity from a miller.

Table 11 Possible solution rankings targeting operational cost

Possible solutions	Priority Weight (%)	Rank
Standardise technical guidelines for biogas installation	71.97	1
Give investors freedom to purchase either locally or imported manufactured technology	28.03	2

Consistency Ratio (CR) = 0.0000

Table 12 shows rankings within the 'revenue' main criterion, demonstrating that 'allowing variations in FiT rate' (34.34%) was ranked highest. Operational costs (both maintenance and labor costs) tend to increase over time. There is a need for more maintenance due to the year-on-year wear and tear of the gas engine. In addition, labor costs increase due to salary increments and bonuses given to workers. This requires the FiT rate to increase over time to maintain profitability and allow the running of the plant for a longer period.

Table 12 Possible solution rankings targeting revenue

Possible solutions	Priority Weight (%)	Rank
Set high, fixed FiT rate	11.32	4
Allow variations in FiT rate	34.34	1
Set FiT rate according to electricity transmission to grid	24.43	3
Introduce new legislation on carbon trading	29.90	2

Consistency Ratio (CR) = 0.07175

4.2.3. Results of the overall ranking

The overall ranking of possible solutions is presented in Fig. 4. 'Providing detailed environmental guidelines' (30.1%) was considered most important overall, followed by 'standardising technical guidelines for biogas installation' (14.0%), 'covering open pond wall using lining' (12.1%), 'enabling private millers to supply waste to a centralised POME waste treatment facility' (8.5%) and 'implementing easy application procedure for ITA' (6.5%). These top five options serve as recommendations for policy targeting the treatment of POME for energy generation.

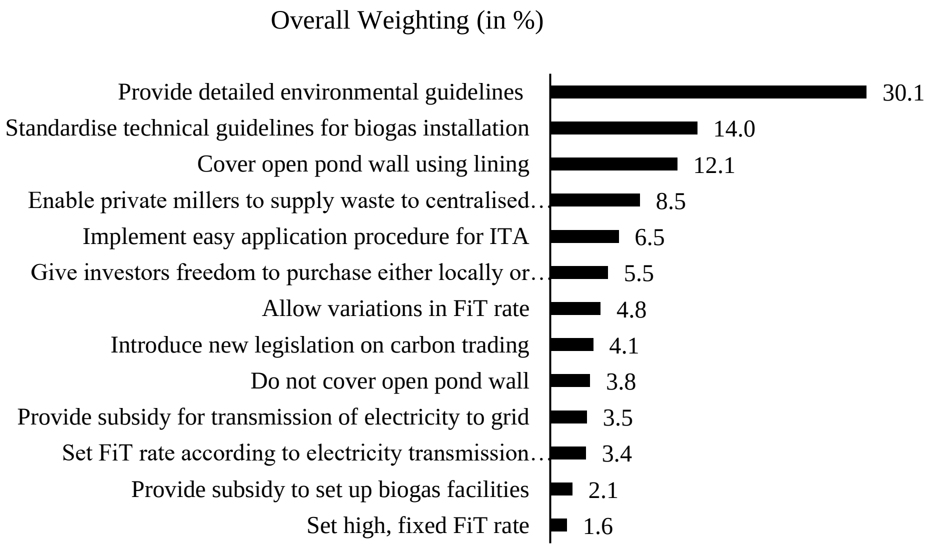

Fig. 4. Overall ranking of possible solutions

5. Discussion and Conclusion

In terms of LCCBA, the CSTR system was found to be more economically feasible than the CLB system. Both systems were capable of generating revenues from the sale of electricity to the grid. The total capital cost of the CSTR system was estimated to be 1.83 Million USD more than the CLB system. Key findings of this study show that:

- The CSTR system has an NPV value of 0.32 Million USD/year more than the CLB system over a 20-year life span.

- The CSTR system has an ROI value of 3.94% higher than the CLB system.
- The CLB system has a PP value of 4.1 years longer than the CSTR system.

In terms of policy development, the most important area to address is the environmental impact. ‘Covering the open pond wall by using a lining’ comes under the ‘environmental impact’ main criterion. The benefit of doing this reduces the eutrophication potential (e.g. [18]) and was seen as a priority. Among the four main criteria, the lowest ranked main criterion is ‘revenue’. This criterion is of the utmost importance to investors [61], but was not the key focus of experts. The highest ranked possible solution under the ‘revenue’ main criterion identified by the AHP is to ‘allow variation in the FiT rate’. However, one expert noted there can be no variation according to current regulations, and the FiT rate is now set based on a bidding process among the millers. It is not possible to ‘vary the FiT’, or to ‘set a high, fixed FiT’ or to ‘set the FiT according to the distance that the electricity has to travel to reach the grid’.

‘New legislation on carbon trading’ which is one of the possible solutions suggested could be introduced in Malaysia to enable millers to claim carbon credits. Currently, to achieve nationally determined contributions under the Paris agreement, 19 emission trading systems (ETSs) have started operating at the national and subnational levels. Developing countries that wish to develop their own ETS are being encouraged to gain insights from the Korean ETS (KETS), as well as schemes in other countries within Asia and the Pacific region [62]. To deliver a carbon price signal against which participants can invest in emission reductions, an efficient carbon market is necessary. The other two possible solutions under the ‘revenue’ main criterion were based on ‘providing a subsidy for biogas installation’ and ‘providing a subsidy for the transmission of electricity to the grid’. However, most of the experts did not agree with these suggestions as the allocation of FiT currently subsidises the cost of investment in the transmission of electricity to the grid. As a whole, some of the possible solutions suggested in relation to the FiT are not viable policy options based on the current situation in Malaysia. The remaining possible solutions could nevertheless be considered and usefully improve current policy on the treatment of POME for energy generation.

Findings presented in this study are crucial for investors deciding on the technologies to be employed in POMs as well as helping decision makers/policy makers to make more effective and efficient decisions. The majority of investors are sceptical when it comes to investing into renewable energy technologies, as the profitability in investing in a new system is fraught with uncertainty [19]. Findings from this study are able to provide useful information reflecting the current situation in Malaysia and can be used to inform investors' decision making. Most previous studies did not perform an in-depth analysis on the economic aspects due to insufficient information, so this study extends previous knowledge on the current situation of POMs in Malaysia.

In this study, the system boundary for both POMs did not cover the usage of sludge for composting; this was due to insufficient information. POMs that sell compost could obtain additional revenue to the system besides the sales of electricity to the grid. The present study was limited to two commercially available POME treatment technologies in Malaysia

Looking into other treatment technologies could provide a wider economic overview of potential options. Some POMs use a portion of the biogas generated to heat the boilers, substituting the usage of palm kernel shells (PKS) [20]. In those cases, unused PKS could be sold, as the unused PKS have a good market value. This could be another contributor to the revenues gained, which could definitely improve the NPV, ROI and PP [20]. As both POMs in this study did not utilise biogas to heat the boilers, future studies may look into POMs with different pathways for better comparison. Data used in this study were mostly obtained from the POMs, except for the excavation costs. Operational and depreciation costs, particularly for POM 2, were estimated based on calculations in the literature [20,36] due to data unavailability. The results would better reflect real, on-the-ground situation if all the values can be obtained directly from the compared mills.

Future researchers may wish to consider social aspects related to job creation, safety and health of workers in addition to the environmental and economic aspects. Further, the number of respondents could be increased, including other relevant stakeholders. This would be especially important at the interview stage when eliciting possible solutions. However, a sample of many respondents may cause greater difficulty in obtaining a consistent output, even using multi-criteria approaches. Finally, adapting another developing country's method [62] as a basis to improve the current policy/regulations in Malaysia could offer a useful way forward. However, it is crucial to ensure that any such regulations suit the Malaysian context. The output of this study from Malaysia will be useful for future researchers both within and external to Malaysia, as it can act as a benchmark for other case studies.

Acknowledgements

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