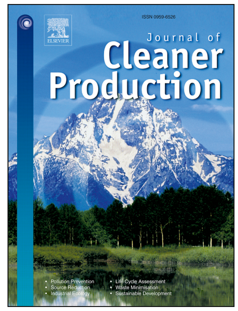

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Towards Circular Economy: Economic Feasibility of Waste to Biomethane Injection through proposed Feed-in Tariff

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Abstract

Lately International Energy Agency (IEA) highlighted the vital role the biogas and anaerobic digester (AD) in the advent of circular economy. Organic residues or waste will be converted into high-value products, power, heating and fuel in the future of bio-economy. This study look specifically into the institutional and market factor, of a Feed-in Tariff (FiT) mechanism as a policy instrument to promote integration of biomethane into existing gas grid. In the circumstance where market is not in the favour of bioenergy/biogas, with fossil fuels are subsidised under national economic policy of the case study in Malaysia; this study found that under the current piped natural gas price, the proposed FiT, 34.02 – 141.79 MYR/GJ (7.13 – 29.73 EUR/GJ) is economically incompetent for biomethane to be injected into the grid without other policy and mandate support. However, natural gas price rationalisation may close the price gap, this is especially for biomethane derived from palm oil mill effluent (POME) and food waste at 4 MW size. Through Net Present Value (NPV) approach, among the four locally available feedstock assessed in this study: POME, food waste, chicken manures and cattle manures; POME and food waste show lower levelised cost due to minimal competing utilisation value in addition to their higher biogas conversion rate. POME prevails as a feedstock choice for its uniform composition and on-site production advantage. Discussion and recommendations based on the current policy scenarios in Malaysia are provided in the section following results and findings.

Keywords: circular economy, biomethane, Feed-in Tariff (FiT), injection, Net Present Value (NPV), POME

Wordcount: 7,347 words

Highlights:

- Four feedstocks are studied: palm oil mill effluent, food waste, chicken manure, cattle manure
- Proposed Feed-in Tariff ranges between 34.02 – 141.79 MYR/GJ (7.13 – 29.73 EUR/GJ)
- Palm oil mill effluent prevails as a feedstock choice for its uniform composition and on-site production advantage

Nomenclature & Symbol

AD	anaerobic digester
AP	acidification potential
atm	atmosphere
BAM	Biogas Association Malaysia
BNM	Bank Negara Malaysia
c	capacity (MW)
CAPEX	capital expenditure
bioCNG	compressed biogas
CBM	compressed biomethane
COD	Chemical Oxygen Demand
CPI	Consumer Price Index
D	transportation distance (km)
E	electricity consumed (kWh/m^3 biomethane)
E_{biogas}	biogas conversion rate (m^3 biogas/m^3 feedstock)
E_{biom}	biomethane conversion rate (m^3 biomethane/t feedstock)
$ElecPrice$	electricity price (MYR/kWh)
EP	eutrophication potential
EUR	EURO
f	feedstock
FC	fuel consumption (L/km)
FiT	Feed-in tariff
GCPT	Gas Cost Past Through
GHG	greenhouse gas
GHV	gross heating value
GJ	gigajoule
GTFS	Green Technology Financing Scheme
GWP	global warming potential
h	hour
HTP	human toxicity potential

IBR	Incentive Based Regulation
IEA	International Energy Agency
km	kilometre
LCA	life cycle analysis
LCOE	levelised cost of energy
LNG	liquified natural gas
m^3	cubic meter
M_f	feedstock equivalent (t/y)
MW	megawatt
MYR	Malaysian Ringgit
NoT	number of trips per year
NPV	Net Present Value
OPEX	operational expenditure
$P_{f,c}^{BM}$	power rating of compressor (kW)
POME	palm oil mill effluent
$Production$	biomethane production of plant (GJ)
psig	pound-force per square inch
PV	photovoltaic
r	discount rate (%)
R & D	research and development
RE	renewable energy
ROI	return of investment
SEDA	Sustainable Energy Development Authority
SIRIM	Standard and Industrial Research Institute of Malaysia
t	anticipated project lifetime (y)
t	tonne
TPA	third party access
USD	US Dollar
V_{BG}	biogas volumetric flowrate (m^3/h)
V_{BM}	biomethane volumetric flowrate (m^3/h)
VS	volatile solid

y	year

1. Introduction

The recent advancement of biogas development has shifted towards demand-based approach, this is especially obvious in more advance economy like in the Germany and Sweden. Purkus et al. (2018) conducted a study to evaluate the feasibility of bioenergy as an energy provider with low-carbon flexibility for future power system as a justification for continued policy support for technology-specific renewable energy (RE) deployment support, taking the case study in Germany. It is found that bioenergy/biogas has high technical potentials as a low-carbon flexibility provider until more information is available on its competitiveness comparing to other low-carbon flexibility options. Goverment support in the form of policy incentives play a crucial role for a continuous technological development of bioenergy/biogas as an option to remain possible. Ammenberg et al. (2018) conducted a demand-side social study with biogas actors to raise awareness and knowledge about regional preconditions for biogas expansion, with a focus on central Swedish region. It is found that the primary reason for decreased biogas development is due to missing long-term national strategy that has caused uncertainties among biogas actors on decision maker's views on biogas. Many respondents/biogas actors declared that policy instrument has a strong influence on biofuels development, among which included biogas. Aligning to results presented by Fenton and Kanda (2017), institutional barrier, which has a central and influential role, remains a challenge for biogas development. Satchwell et al. (2018) conducted a study to identify scientific, operational and policy solutions that are needed to address the barriers for greater AD deployment, among which included technical, regulatory and economic barriers, taking the case of U.S. It is advised that inter-disciplinary research, operational improvement, regulatory policies advancement and supportive financial incentives are needed to accelerate the deployment of AD. In France, the energy policy has an ambitious target of biomethane feed into the national grid at 8 TWh per year by 2023. Herbes et al. (2018) conducted qualitative interviews to explore French consumers' knowledge and attitudes towards biogas. It is found that there is generally a preference towards biomethane produced from agricultural residues and biodegradable household waste, but not products derived from energy crops. A higher awareness and knowledge would help consumers to make a more informed evaluation on products derived from biomethane. It is also advised that policy makers can encourage biomethane injection into the grid by removing financial obstacles surrounding its deployment. When biomethane utilisation for vehicle fuel is compared over for grid injection for small scale plant in Italy, both resembles similar energy efficiency of 87.3 % and 89.8 % respectively. The unit cost of production of biomethane is 0.54 EUR/m^3 for grid injection while it is 0.73 EUR/m^3 for vehicle fuel under Italian legislative framework (Rotunno et al., 2017).

Meanwhile in developing country, Nevzorova and Kutcherov (2019) found that economic barrier has higher influence on biogas development when compared to developed countries due to high investment and lack of available capital. Mittal et al. (2018) conducted a study to identify barriers for biogas deployment in India. Despite having a potential production of 29 - 49 x 10^9 m^3/year, the current biogas production in India is only at 2.07 x 10^9 m^3/year. It is found that financial barrier remains the main obstacle for biogas dissemination in India, among which included high upfront cost of technology installation, difficulty in getting loan from financial institutions. It is advised that provision of micro-finance, low-cost credits could spur biogas uptake in India. It is noted that electricity produced from biogas also faced competition from other renewables, thus it is recommended that a preferential tariffs or minimum purchase quota to be provided by the government to reduce market risks faced by biogas producers. Other than economic reason, institutional and organisational also hinder biogas development. Lönnqvist et al. (2018) analysed conditions that enable systematic transition from sorted household waste into integrating large-scale biogas generation with current waste management system in Bolivia. The biogas development is more affected by the system that is influencing its adoption and technological transfer from developed countries to developing countries. It is found that in Bolivia, other than economic barrier, institutional and organisational barrier could also affect systematic transition into renewable energy, for instance, heavy fossil fuel subsidies in Bolivia despite the lack of incentives to promote biogas.

Narrowing down to regional biogas development, Quek et al. (2018) examined the sustainability of transition to renewable energy systems from a fossil fuel-dependent electricity system through life cycle approach with four major environmental impacts were considered: global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP) and eutrophication potential (EP). Various electricity supply sources are considered: solar photovoltaics (PV), biogas, waste incineration, natural gas, coal and oil. Singapore energy system, with more than 95 % mix of natural gas, is used as a baseline for comparison under different RE mix scenarios. For biogas, it is found that despite having lower GWP, the cradle-to-gate analysis shows that having higher proportion of biogas in power generation can produce eight times higher AP and EP than baseline. AP of biogas especially has a regional impact. Looking into the life cycle analysis (LCA) of biogas, majority of AP is due to the impact of crop farming, attributing to chemical fertilizers used (about 80 %). However, the authors have also emphasised that the validity of results depend on local practice which could reduce AP significantly. For instance, biogas production from wastewater treatment plants or biomass residue which resembles carbon neutrality/negativity in a form of GHG mitigation. Loh et al. (2017) conducted a study to demonstrate Malaysia's experience on biogas capture and utilisation from waste water sources under the nation Economic Transformation Programme and highlighted the crucial interdisciplinary role of technological, financial and institutional elements in putting biogas plan into implementation. Speaking of other potential application of POME-based biogas, Loh et al. (2017) suggested that it is possible for upgraded biogas, in the form of compressed biogas (bioCNG) can be used to replace fuel oil in industrial processes by feeding the upgraded biogas into existing natural gas pipeline/grid or transport to the intended end users in bottle. Hoo et al. (2018) investigated the trade-off between pressure requirement and distance of supply-demand of biomethane injection (upgraded biogas/landfill gas) into natural gas grid, taking the case study in Malaysia. It is found that upgraded biogas remains economically uncompetitive to be injected into natural gas grid although there is a potential to fulfil industrial demand. This is partly due to market barrier with fossil natural gas as a cheaper option. Unless there is incentive for biogas sales and a market instrument that turns the environmental liability of methane gas emitted from biomass residue/landfill into economic opportunity, biogas would remain handicapped from competing with natural gas, especially when the latter option is highly subsidised. This is also observed in a study conducted by Lönnqvist et al. (2018) where heavily subsidised fossil fuel forms the barrier for large-scale biogas integration. A policy instrument remains crucial for biogas deployment by improving its market competitiveness.

The uptake of biogas is a complicated process where many factors influence simultaneously, namely, technical factor, economical factor, market influence, institutional factor, social cultural factor and environmental factor (Nevzorova and Kutcherov, 2019). Based on the rational from reviewed literature, this paper will look specifically into the institutional and market factor, of a FiT mechanism which has proven successful in some cases (Purkus et al., 2018) as a policy instrument to promote integration of biomethane into existing gas grid. This study addresses the current issue of policy landscape surrounding the facilitation of enhanced biogas development in a developing economy where the market is not in the favour of bioenergy/biogas, this is especially under national economic policy that subsidises fossil fuels. A novel approach to address spatial logistical, economic and market constraint challenge in matching biogas supply, which is abundantly found in remote area to demand at industrial area through injection station by analysing the price gap and country's policy and market circumstances is proposed. The current state-of-the-art of biogas adoption studies conducted in the region has minimal studies that took an interdisciplinary approach to analyse this issue. Techno-economic barrier, market barrier and institutional barrier are assessed in this study. A policy instrument, the Feed-in Tariff mechanism is proposed for biomethane injection into natural gas grid through Net Present Value (NPV) approach. Four different feedstocks: POME, food waste, cattle manure and chicken manure are studied with various injection modes are considered. Section 2 will present the method used in this study; Section 3 will explain the case study based on different feedstocks considered; Section 4 will present and discuss the results; Section 5 will describe the recommendations to overcome the challenges of biogas development; lastly conclusion will be presented in Section 6.

2. Method

Judging from the success of electricity FiT scheme in Malaysia in promoting penetration of renewable energy, fixed rate method (Couture et al., 2010) is adopted to estimate the FiT for biomethane injection into natural gas grid. Section 2.1 will discuss about the equations involved in the model to estimate FiT for biomethane by assuming Net Present Value (NPV) equals to zero. Section 2.2 will describe the parameters that are involved in capital expenditure (CAPEX) and operational expenditure (OPEX) estimation of biomethane upgrading and injection plant. Energy unit GJ is used to represent capacity instead of volumetric unit as this chapter involves comparison among biomethane with two different compressed pressure and energy content.

The assumptions involved in this study included:

1. The project life is taken at 25 years at interest rate of 5 %;

2. All cost are adjusted to Malaysian Ringgit at year 2018 this study were to study feasibility of biomethane injection into natural gas grid through FiT scheme;
3. It is assumed that biomethane project is located near to where natural gas pipeline is available (50 km distance radius for pipeline transportation; 100 km distance radius for virtual pipeline transportation).

2.1 Feed-in Tariff (FiT) Calculation

There are many different types of FiT designs, for example, FiT design with purchase obligation, FiT design with stepped tariff, FiT design with tariff digression, FiT design with premium option, FiT design with equal burden sharing and FiT design with forecast obligation. It is also important to determine the tariff level and duration of support. Minimum tariff level can be designed by identifying the levelised cost of energy (LCOE) of biomethane. LCOE is the net present value of a unit cost of gas produced over a lifetime of the generating facility. In order to obtain LCOE, NPV is used to calculate the minimum tariff rate by assuming NPV equals to zero, which it indicates no gain nor loss for the plant lifetime operation, as shown in Equation (1) (Lim et al., 2015). In this study, LCOE is computed for all feedstock *f* at capacity *c* based on Equation (1).

$$NPV_{f,c} = \frac{\sum_0^n \left(\frac{Production_{f,c} \times FiT_{f,c}}{year} - \frac{OPEX_{f,c}}{year} \right)}{(1+r)t} - CAPEX_{f,c} \quad (1)$$

Where:

NPV	=	Net Present Value
$Production$	=	Biomethane production of plant (GJ)
$OPEX$	=	Total operational and maintenance cost (MYR/y)
FiT	=	Feed-in Tariff (MYR/GJ)
r	=	discount rate (%)
t	=	anticipated project lifetime (y)
$CAPEX$	=	Total capital cost (MYR/y)

When NPV is assumed at zero, it indicates all cash inflows and outflows reach at breakeven point, it is also the minimum earning without causing losses to the investors. The project life is projected for 25 y, at discount rates varying at 0.05, 0.1 and 0.15.

2.2 CAPEX and OPEX of Biomethane Transportation Configuration

There are three biomethane transportation configurations compared in this study:

1. Biomethane upgraded from upgrader is injected into natural gas distribution grid by physical pipeline of 8-in diameter at 20 psig;

2. Biomethane upgraded from upgrader is injected into natural gas grid by virtual pipeline, which is compressed biomethane transported through trailer at 250 psig. Figure 1 shows the working principle of a virtual pipeline (Galileo Technologies, 2014). A commercialised virtual pipeline usually consists of three interdependent components, namely the mother station (compression), the transportation and the consumption station / gas district station, where compressed biomethane (CBM) is injected into the natural gas pipeline. The storage box design of a virtual pipeline allows gas to be stored prior to use.

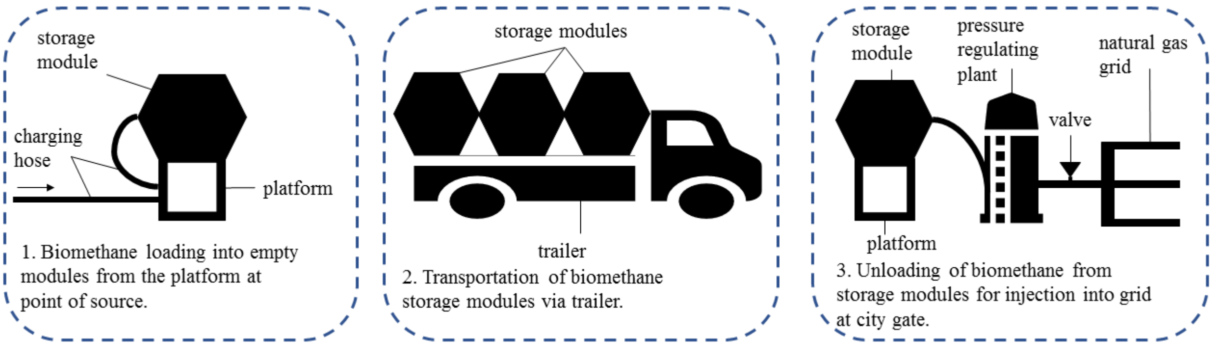

Figure 1 Working principle of a virtual pipeline

3. Biomethane upgraded from upgrader is directly sold to third party gas distribution company by paying the transmission tariff.

Equations of the total CAPEX calculation for each configuration are as shown in Equation (2), Equation (3) and Equation (4):

$$TotCAPEX_{f,c}^{VP} = (CAPEX_{AD} \times V_{f,c}^{BG}) + (CAPEX_{Up} \times V_{f,c}^{BG}) + (CAPEX_{Com} \times P_{f,c}^{BM}) + (CAPEX_{IF} \times V_{f,c}^{BM}) + CAPEX_{VP} + Cost_{feedstockSP} \quad (2)$$

$$TotCAPEX_{f,c}^{P} = (CAPEX_{AD} \times V_{f,c}^{BG}) + (CAPEX_{Up} \times V_{f,c}^{BG}) + CAPEX_{Com} + (CAPEX_{IF} \times V_{f,c}^{BM}) + (CAPEX_{P} \times D) + Cost_{feedstockSP} \quad (3)$$

$$TotCAPEX_{f,c}^{T} = (CAPEX_{AD} \times V_{BG}) + (CAPEX_{Up} \times V_{BG}) + CAPEX_{Com} + Cost_{feedstockSP} \quad (4)$$

Where;

$TotCAPEX_{VP}$ = Total CAPEX of biomethane transported via virtual pipeline (MYR)

$TotCAPEX_{P}$ = Total CAPEX of biomethane transported via pipeline (MYR)

$TotCAPEX_{T}$ = Total CAPEX of biomethane transported via distributor (MYR)

$CAPEX_{AD}$ = Capital cost of anaerobic digester (MYR/kW)

$CAPEX_{Up}$ = Capital cost of upgrader (MYR/(m^3/h biogas))

$CAPEX_{Com}$ = Capital cost of compressor (MYR)

$CAPEX_{IF}$ = Capital cost of injection facility (MYR/kW)

$CAPEX_{VP}$ = Capital cost of virtual pipeline (MYR)

$CAPEX_{P}$ = Capital cost of stainless steel pipeline (8-in diameter) (MYR/km)

$Cost_{feedstockSP}$ = Feedstock storage and preparation cost (MYR)

D = Transportation distance (km)

$P_{f,c}^{BM}$ = Power rating of compressor (kW)

V_{BG} = Biogas volumetric flowrate (m^3/h)

V_{BM} = Biomethane volumetric flowrate (m^3/h)

The yearly OPEX components for each biomethane transportation configurations are as shown in Equation (5), Equation (6) and Equation (7).

$$TotOPEX_{f,c}^{VP} = (OPEX_{AD} \times V_{f,c}^{BG}) + (OPEX_{Up} \times V_{f,c}^{BG}) + (V_{f,c}^{BM} \times E \times ElecPrice) + (OPEX_{IF} \times V_{f,c}^{BM}) + (NoT \times D \times FC \times Cost_F) + (M_f \times Cost_{Feed}) + Cost_{Mis} \quad (5)$$

$$TotOPEX_{f,c}^{P} = (OPEX_{AD} \times V_{f,c}^{BG}) + (OPEX_{Up} \times V_{f,c}^{BG}) + (V_{f,c}^{BM} \times E \times ElecPrice) + (OPEX_{IF} \times V_{f,c}^{BM}) + (OPEX_P \times D) + (M_f \times Cost_{Feed}) + Cost_{Mis} \quad (6)$$

$$TotOPEX_{f,c}^{T} = (OPEX_{AD} \times V_{f,c}^{BG}) + (OPEX_{Up} \times V_{f,c}^{BG}) + (V_{f,c}^{BM} \times E \times ElecPrice) + (Cost_T \times V_{f,c}^{BM}) + (M_f \times Cost_{Feed}) + Cost_{Mis} \quad (7)$$

Where;

$TotOPEX_{VP}$ = Total CAPEX of biomethane transported via virtual pipeline (MYR/y)

$TotOPEX_P$ = Total CAPEX of biomethane transported via pipeline (MYR/y)

$TotOPEX_T$ = Total CAPEX of biomethane transported via distributor (MYR/y)

$OPEX_{AD}$ = Operational cost of anaerobic digester (MYR/kW)

$OPEX_{Up}$ = Operational cost of upgrader (MYR/(m^3/h biogas))

$OPEX_{IF}$ = Operational cost of injection facility (MYR/kW)

$OPEX_{VP}$ = Operational cost of virtual pipeline (m^3/trip)

$OPEX_P$ = Operational cost of pipeline (MYR/km)

$Cost_T$ = Transmission cost (MYR/kWh)

E = Electricity consumed (kWh/m^3 biomethane)

$ElecPrice$ = Electricity price (MYR/kWh)

NoT = Number of trips per year

FC = Fuel consumption (L/km)

M_f = Feedstock equivalent (t/y)

$Cost_{Feed}$ = Feedstock cost (MYR/t)

$Cost_F$ = Fuel cost (MYR/L)

$Cost_{Mis}$ = Miscellaneous cost which included digestate handling cost, labour cost, services, insurance, taxes, pH control and biogas cleaning (MYR/y)

3. Case Study

3.1 Biomethane Volumetric Flowrate from each Feedstock

In this section, the required volume of biogas and biomethane for each feedstock: POME, food waste, chicken manure, cattle manure will be elaborated. It is important to identify the amount of feedstock needed based on specific biogas conversion rate of respective feedstock. For the same amount of biomethane injection, different feedstock will have different characteristics (pH, nutrient and chemical composition) that affects its biogas conversion rate, thus giving different amount of feedstock required to produce the same amount of biogas, which eventually affect the cost of feedstock storage and preparation. Equation (8) (when biogas conversion rate is available) and Equation (9) (when biomethane conversion rate is available) show the equivalent biomethane/biogas conversion from feedstock.

$$M_f = \frac{V_{BG}}{E_{biogas} \times 365 \times 24} \tag{8}$$

Where:

E_{biogas} = Biogas conversion rate (m^3 biogas/m^3 feedstock)

$$M_f = \frac{V_{BM}}{E_{biom} \times 365 \times 24} \tag{9}$$

Where:

E_{biom} = Biomethane conversion rate (m^3 biomethane/t feedstock)

It is assumed that all biogas and biomethane volumes are measured at 1 atm, room temperature.

3.1.1 POME

Table 1 shows the required volumetric flowrate of food waste biogas, calculated based on energy conversion, with 8,760 operating hours per year at 0.8 capacity factor. For every unit m^3 of POME digested, 25 m^3 is produced. POME biogas has an energy content of 22 MJ/m^3 (Sarawak Energy, 2013), while the gross heating value (GHV) of biomethane is 37.8 MJ/m^3 (Wellinger et al., 2013).

Table 1 Required POME biogas and biomethane volumetric flowrate

Capacity (MW)	Annual production (MJ/y)	Biomethane equivalent (m^3/h)	POME biogas equivalent (m^3/h)	POME equivalent (m^3/y)
4	100,915,200	304.76	523.64	183,482
10	252,288,000	761.90	1,309.09	458,705
30	756,864,000	2,285.71	3,927.27	1,376,116

3.1.2 Food waste

Table 2 shows the required volumetric flowrate of food waste biogas, calculated based on energy conversion, with 8,760 operating h per y at 0.8 capacity factor. For every unit m^3 of food waste biogas produced, it contains 0.75 m^3 biomethane (Kumaran et al., 2016). For every unit kg volatile solid (VS) digested, with 0.95 VS content per kg food waste, 0.55 m^3 biogas is produced (Kumaran et al., 2016). VS is the solid materials found in liquid state that are combustible at 550 □, which is a useful indicator of amount of organic matter present in sewage sludge or food waste.

Table 2 Required food waste biogas and biomethane volumetric flowrate

Capacity (MW)	**Annual production (MJ/y)**	**Biomethane equivalent (m^3/h)**	**Food waste biogas equivalent (m^3/h)**	**Food waste equivalent (t/y)**
4	100,915,200	304.76	401.04	6,724
10	252,288,000	761.90	1,002.61	16,809
30	756,864,000	2,285.71	3,007.83	50,428

3.1.3 Chicken Manure

Table 3 shows the required volumetric flowrate of biogas generated from chicken manure, calculated based on energy conversion, with 8,760 operating h per y at 0.8 capacity factor. Every unit kg of chicken manure can produce 0.05 m^3 of biomethane (Kumaran et al., 2016).

Table 3 Required chicken manure and biomethane volumetric flowrate

Capacity (MW)	**Annual production (MJ/y)**	**Biomethane equivalent (m^3/h)**	**Chicken manure equivalent (t/y)**
4	100,915,200	304.76	52,697
10	252,288,000	761.90	131,743
30	756,864,000	2,285.71	395,229

3.1.4 Cattle Manure

Table 4 shows the required volumetric flowrate of biogas generated from cattle manure, calculated based on energy conversion, with 8,760 operating h per y at 0.8 capacity factor. 0.032 m^3 biogas is produced for every unit kg cattle manure digested. For every unit m^3 of cattle manure biogas produced, it contains 0.65 m^3 biomethane (Kumaran et al., 2016).

Table 4 Required cattle manure and biomethane volumetric flowrate

Capacity (MW)	Annual production (MJ/y)	Biomethane equivalent (m^3/h)	Cattle manure biogas equivalent (m^3/h)	Cattle manure equivalent (t/y)
4	100,915,200	304.76	523.64	183,482
10	252,288,000	761.90	1,309.09	458,705
30	756,864,000	2,285.71	3,927.27	1,376,116

3.2 Economic Parameters

Table 5 and Table 6 show the CAPEX components and OPEX components involved in this study. Feedstock cost are also included in Table 6, cost for POME and food waste are assumed at zero cost as these wastes have no market value in the studied area.

Table 5 CAPEX components of biomethane injection into natural gas grid

	Unit value	References
Sizes		
CAPEX components		
Anaerobic digester		
- < 500 m^3/h raw biogas	11,838 MYR/kW	(Loh et al., 2017)
- 500 – 2,000 m^3/h raw biogas	18,905 MYR/kW	
Upgrader		
- < 500 m^3/h raw biogas	6,000 MYR/(m^3/h raw biogas)	Personal communication
- 500 – 2,000 m^3/h raw biogas	4,000 MYR/(m^3/h raw biogas)	
Compressor		
- 20 psig	7.72 MYR/kW	(Lee et al., 2019)
- 250 psig	44.62 MYR/kW	
Injection facility		
- 350 m^3/h	2.01 MYR cents/kWh	(Wellinger et al., 2013)
- 700 m^3/h	1.04 MYR cents/kWh	(Wellinger et al., 2013)
Transportation means		
- Virtual pipeline (> 50km)	0.16 MYR/m^3	(Galileo Technologies, 2014)
- Pipeline (50 km)	479,897 MYR/km	(Menon, 2005)

Table 6 OPEX components of biomethane injection into natural gas grid

	Unit value	References
Sizes		
OPEX components		
Anaerobic digester		
- < 500 m^3/h raw biogas	2% of CAPEX	(Loh et al., 2017)
- 500 – 2,000 m^3/h raw biogas	2 % of CAPEX	
Upgrader		
- < 500 m^3/h raw biogas	2 % of CAPEX	Personal communication
- 500 – 2,000 m^3/h raw biogas	2 % of CAPEX	
Injection facility		
- 350 m^3/h	1.87 cents MYR/kWh	(Wellinger et al., 2013)
- 700 m^3/h	1.51 cents MYR/kWh	(Wellinger et al., 2013)
Transportation means		
- Virtual pipeline (50km)	2.18 MYR/L	(How et al., 2016)
- Pipeline (50 km)	19,092 MYR/km	(Menon, 2005)
- Transmission charge	0.0050 MYR/kWh	(Petronas Gas Berhad, 2011)
Feedstock		
- POME	0	N/A
- Food waste	0	N/A
- Chicken manure	9.8 MYR/kg	Personal communication
- Cattle manure	9.8 MYR/kg	Personal communication
Electricity price	0.34 MYR/kWh	(Energy Commission, 2017)
Miscellaneous	10% of overall OPEX	-

It is noted that all values are adjusted to latest inflation rate in 2018. Table 7 shows the compiled Consumer Price Index (CPI) that is used to adjust each value from Bank Negara Malaysia (BNM). Table 8 shows the exchange rate of Malaysian currency from 2006 to 2018 (Bank Negara Malaysia (BNM), 2018).

Table 7 Malaysia CPI

Year (2000)	’06	’07	’08	’09	’10	’11	’12	’13	’14	’15	’16	’17	’18
CPI	90.86	92.7	97.75	98.32	100.02	103.19	104.91	107.12	110.48	112.81	115.18	117.60	122.07

Table 8 Exchange rate

Year	USD/MYR	EUR/MYR
2006	3.6671	4.6088
2008	3.3319	4.8954
2009	3.5236	4.9108
2010	3.2182	4.2691
2011	3.0594	4.2582
2012	3.0898	3.9709
2013	3.1511	4.1849
2014	3.2736	4.3479
2015	3.9073	4.3336
2016	4.1457	4.5865
2017	4.3008	4.8530
2018	3.9382	4.7676

All CAPEX are then annualised over 25 years of loan payment at 5 % interest rate.

4. Result and Discussion

Results of the model will be discussed based on the three different transportations modes of biomethane. Section 4.1 discusses about the LCOE of biomethane transported by virtual pipeline; section 4.2 discusses about the LCOE of biomethane transported by pipelines; section 4.3 discusses about LCOE of biomethane transported by third party distributors. Lastly, section 4.4 will compare and verify the results obtained with other countries.

4.1 Biomethane Transported by Virtual Pipelines

In order to promote RE share of the country, with a goal of 20 % RE share by 2025, Malaysian government has been running numerous efforts through policy and regulation enforcement, programs and incentives mechanism, among all, the FiT mechanism has proven the biggest success. FiT is a secure mechanism that ensures business sustainability by providing project owner consistent return of investment (ROI). Despite the fact that over support of government incentives could distort the energy market (NREL, 2016), so far the fixed rate FiT implemented in Malaysia has shown negligible influence to the energy market, as it does not significantly increase the electricity bill that consumers are paying (1.6 % surcharge of electricity bill effective on year 2014). Lately the Malaysia government has released 114.57 MW of FiT quota where biogas is allocated with 30 MW quota (SEDA, 2018a). There has been debate ongoing among the industry players on the possibility of biomethane (upgraded biogas) injection into the natural gas grid. This study investigates the economic feasibility of biomethane injection into the natural gas grid through LCOE calculation. FiT for biomethane injection is then estimated based on the levelised cost.

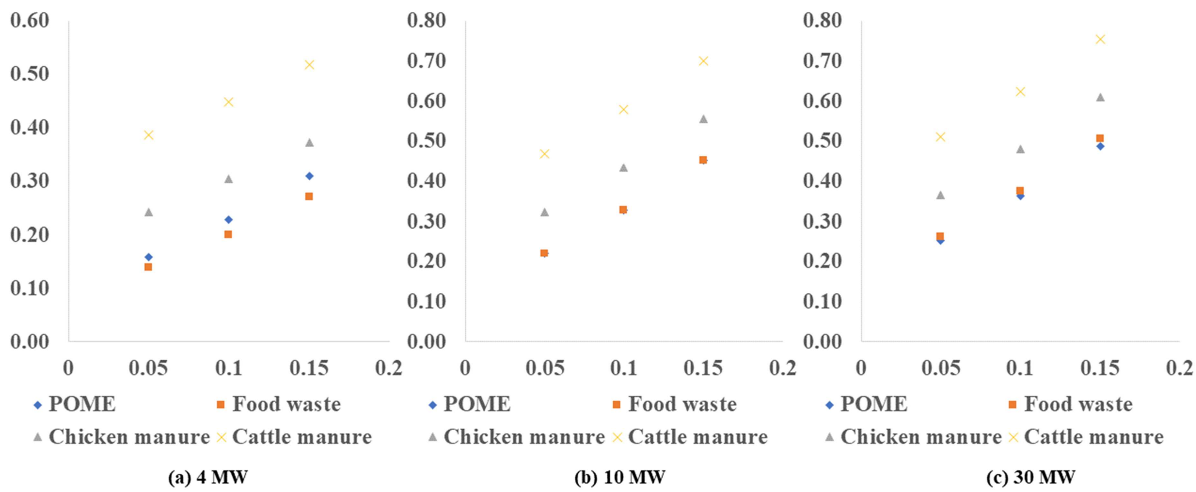

Figure 2 LCOE for biomethane transported by virtual pipeline

Figure 2 shows the LCOE of biomethane injection into the natural gas grid through virtual pipeline. The LCOE ranged between 0.16 – 0.52 MYR/kWh for 4 MW size; 0.22 – 0.70 MYR/kWh for 10 MW size and 0.25 – 0.75 for 30 MW size. LCOG generally increases as discount rate increases (0.05 – 0.15). POME and food waste show relatively smaller LCOE value (0.16 MYR/kWh and 0.14 MYR/kWh respectively at 4 MW, 0.05 discount rate) as compared to the other feedstocks because both feedstocks are obtained in the form waste which has minimal market value. Food waste has lower LCOE than POME as it has high VS content which translates into high biogas conversion, resulting in only small amount of food waste is needed for AD, upgrading and compression. However, while POME is produced at industrial scale and can be collected on-site for biogas generation, food waste will need to be collected from scattered sources. The logistical collection cost of food waste will weigh on the production cost of biomethane. Furthermore, POME resembles a uniform feedstock composition, thus making monitoring of biogas generation more predictable when compared to food waste varying composition. POME with its high Chemical Oxygen Demand (COD) content make it a more productive AD feedstock when compared to chicken and cattle manure. However, POME generation at most mills in Malaysia are only suitable for 4 MW injection capacity, only mills with more than 460,000 m^3/y POME generation are suitable for 10 MW capacity, bigger capacity than 10 MW can only be achieved through clustering POME from a few mills however transportation of POME out of the mills is limited by social, logistic and regulation constraints.

4.2 Biomethane Transported by Pipelines

Figure 3 shows biomethane injection into natural gas grid via 8-in-diameter pipeline injection (20 psig). At 0.05 discount rate, it is observed that LCOE increases from 0.22 to 0.26 MYR/kWh for POME; 0.20 to 0.26 MYR/kWh for food waste; 0.31 to 0.37 MYR/kWh for chicken manure; 0.45 to 0.51 for cattle manure in between 4 MW to 30 MW capacity. Base on the result, 4 MW remains the least LCOE, ranging in between 0.22 – 0.45 MYR/kWh for POME; 0.20 – 0.41 MYR/kWh for food waste; 0.31 to 0.51 MYR/kWh for chicken manure and 0.45 – 0.65 MYR/kWh for cattle manure. It is observed that at 30 MW injection capacity, LCOE for biomethane injection via pipeline and virtual pipeline for food waste, chicken manure and cattle manure are approximately same to each other (± 0.0001 MYR/kWh), that is 0.26 – 0.51 MYR/kWh for food waste; 0.37 – 0.61 MYR/kWh for chicken manure and 0.51 – 0.75 MYR/kWh for cattle manure.

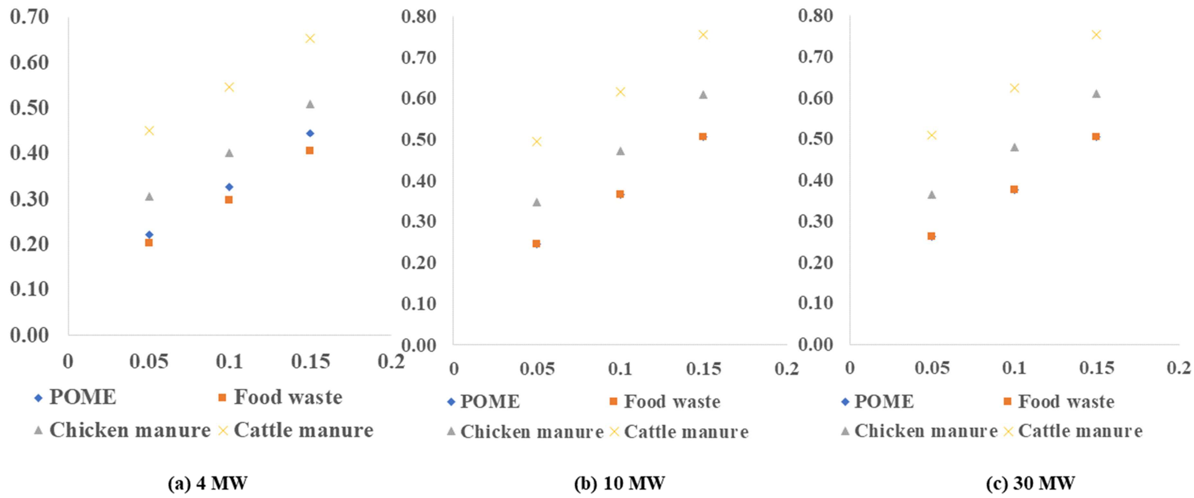

Figure 3 LCOE for biomethane transported by pipeline

Cattle manure has higher LCOE as compared to chicken manure as it has lower methane production (0.02 m^3 biomethane/kg cattle manure) as compared to chicken manure (0.05 m^3 biomethane/kg chicken manure) in order to produce the same amount of biomethane.

4.3 Biomethane Transported by Distributors

LCOE of biomethane injection into natural gas grid via distributors shows rather uniform value as compared to the previous two transportation modes (Figure 4). In this scenario, it is assumed that there is a third party, which is the distributor who owns extensive gas pipelines that could reach to the biomethane producers. Distributor charges the biomethane producer a certain amount of gate fee, for instance, 1.25 MYR/GJ (Petronas Gas Berhad, 2011) for transporting biomethane to the injection point from source of production. Results shows that the overall LCOE are lower than biomethane transported by self-owned infrastructure, averaging at 0.01 - 0.05 MYR/kWh when compared to virtual pipeline transportation, and more than 0.05 MYR/kWh when compared to pipeline transportation. The energetic efficiency of this transportation mode could be the highest when the optimal network configuration is identified (Ng and Maravelias, 2017). Biomethane transported via distributor makes better economic sense as the third party distributor can provide services to more biomethane producers, utilising the infrastructure optimally while making profit by providing gas transportation service. The third party distributor could also come in the form of a market mechanism, where carbon mitigated from biogas capture and conversion, or renewable gas certification will be traded for monetary value that can compensate for the transportation cost of biomethane for off-site usage.

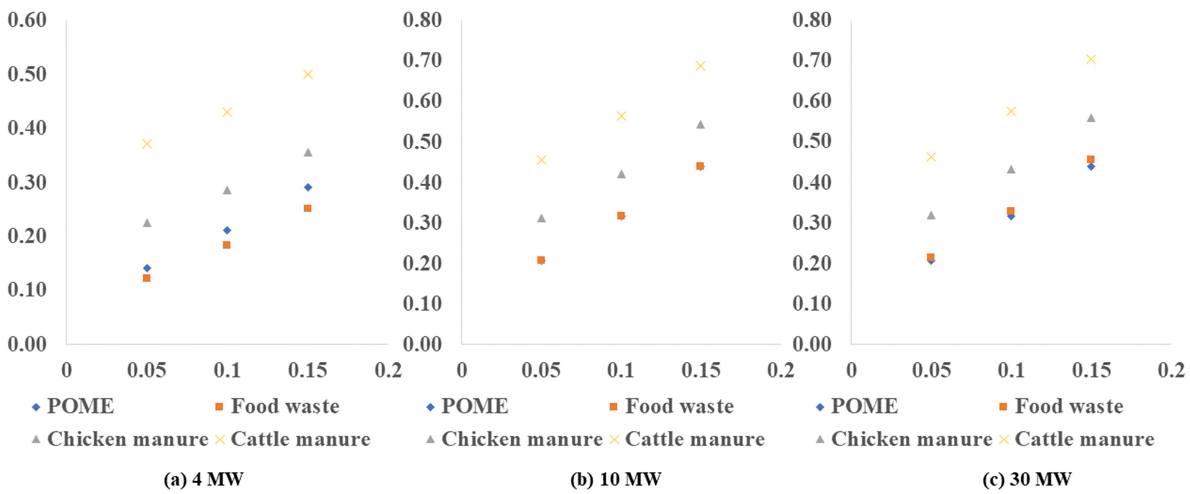

Figure 4 LCOE for biomethane transported by distributors

4.4 Comparison and Verification

The results of the calculated LCOE indicates the minimum FiT of biomethane injection into natural gas distribution grid. The proposed FiTs are then compared to the gas tariff in Peninsular Malaysia from 2015 to 2018 (Figure 5), with projection to 2019 (Gas Malaysia Berhad, 2015). Under the national subsidy rationalisation plan, subsidised piped gas price is adjusted two times annually until it reaches parity with liquefied natural gas (LNG), which is in line with the Incentive Based Regulation (IBR) framework. Under IBR, gas price will be adjusted through Gas Cost Pass Through (GCPT) mechanism every six months starting from 2017.

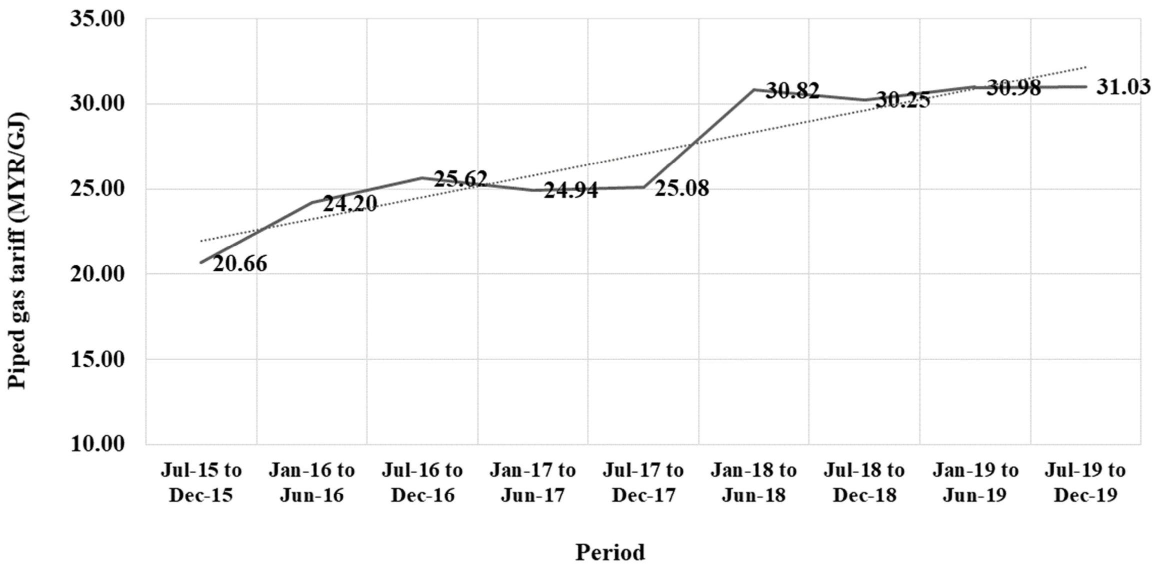

Figure 5 Average piped gas tariff for non-power sector in Peninsular Malaysia (Gas Malaysia Berhad, 2015)

From Table 9, it is observed that the proposed FiT is almost 1.34 to 4.91 times the average piped natural gas price in Peninsular Malaysia. Taking the average piped gas tariff from 2017 to 2019, that is 28.85 MYR/GJ. The price gap shown that it is highly impossible for biomethane to be market competitive under current scenario. Under the national subsidy rationalisation plan, the price gap between biomethane and piped natural gas could be narrowed down, especially for POME and food waste derived biomethane at 4 MW size (green zone), however it is unlikely for piped natural gas price to reach 62.74 – 125.19 MYR/GJ for biomethane derived from animal manures to be competitive (red zone). The proposed FiT is then compared with the FiT rate in France, UK and Austria, where these countries have biomethane plants that inject biomethane into the natural gas grid (Table 10). These countries generally have higher piped natural gas price than Malaysia, that is 48.28 MYR/GJ for France, 31.96 MYR/GJ for UK and 45.71 MYR/GJ for Austria. The proposed biomethane FiT is compared in terms of ratio of biomethane FiT to piped natural gas price: the lower the ratio value, the more attractive and feasible for biomethane injection into natural gas grid. Among all, France has the lowest ratio, due to its high piped gas price (48.28 MYR/GJ). UK has the most generous biomethane FiT, 23.99 – 52.95 MYR/GJ, however, due to its relatively lower piped gas price, 31.96 MYR/GJ, the ratio of biomethane FiT to piped gas price resembles between 0.75 to 1.69.

Transportation mode	Feedstock	FiT (MYR/GJ) 4 MW	10 MW	30 MW
Virtual pipeline	POME	43.94	61.22	70.46
	Food waste	38.70	61.22	72.71
	Chicken manure	67.42	89.94	101.43
	Cattle manure	107.74	130.26	141.75
Pipeline	POME	61.39	68.16	72.75
	Food waste	56.15	68.16	72.75
	Chicken manure	84.87	96.88	101.47
	Cattle manure	125.19	137.20	141.79
Distributor	POME	39.26	57.84	57.47
	Food waste	34.02	57.84	59.72
	Chicken manure	62.74	86.56	88.44
	Cattle manure	103.06	126.88	128.76

Table 9 FiT-to-Gas Tariff ratio

Table 10 Comparison of biomethane FiT among countries

Countries	Piped Gas Price (MYR/GJ)[a]	Biomethane FiT (MYR/GJ)[b]	Ratio of biomethane FiT to piped gas price
Malaysia (proposed)	28.85	38.70 – 141.79	1.34 – 4.91
France	48.28	6.05 – 9.08	0.13 – 0.19
UK	31.96	23.99 – 52.95	0.75 – 1.69
Austria	45.71	7.36 – 9.50	0.16 – 0.21

[a]Piped gas price of France, UK and Austria are obtained from Eurostat (2017).

[b]Biomethane FiT of France, UK and Austria are obtained from RES LEGAL (2011).

It is recommended that further validation to be carried out for the proposed FiT by comparing the rate to biomethane FiT to rationalised natural gas price as currently natural gas price in Malaysia is still subsidised which makes it relatively cheaper than the market price. Besides, as the data are mostly collected from international sources, it is expected the CAPEX and OPEX of biomethane plants can be further reduced when the equipment are designed and fabricated by local biomethane experts. Having learnt from previous lesson on electricity feed into electricity grid in Malaysia, where FiT was implemented along with collection of 1 % (2011) then 1.6 % (2014) surcharge from the power consumers (Leong, 2014), a viable surcharge should be imposed on piped natural gas consumers from non-power sector in order to make the FiT mechanism works for biomethane injection too. Consultation should be carried out with industry players on the proposed FiT for adjustment and additional support, for example, initial investment subsidy, tax reduction and renewable gas certification from the government in order to ensure sustainable growth in the biomethane injection to grid.

5. Recommendations

Currently biogas development in Malaysia remains on renewable energy promotion through bided FiT and sell to national electricity grid. However there remains some barriers for further uptake of biogas, either through injection into the grid or upgraded for use as vehicle fuels, some policy recommendation is drawn from the findings of this study and author's previous work on biogas development in Malaysia. The recommendations can be categorised according to five categories: economic incentive, market competition, institutional support, research and development (R & D) and awareness education.

Previous work has shown that simultaneous implementation of carbon price with fuel subsidy rationalisation are needed to make biomethane injection into natural gas grid economically feasible (Hoo et al., 2019). This finding is also supported by case studies found in countries with successful biomethane penetration into the market, for instance, biomethane utilisation in Italy. Expansion of biomethane injection into gas grid requires upgrading of biogas quality (Satchwell et al., 2018). High cost of installing biogas processing units: pre-treatment, anaerobic digestor, conditioning and purifying unit are among the financial barrier for biogas dissemination (Bong et al., 2017). It is suggested that incentive for technology adoption should be provided to promote deployment of renewable energy technology, in this case, biogas upgrading and injection into natural gas grid (Hoo et al., 2018). A study conducted by Kost et al. (2013) revealed that the managing and maintaining of biogas plants usually involved high cost which would further increase the challenges of biogas owners to operate biogas plants. Even in country with relative advance and high penetration of biogas like in Germany, the LCOE of biogas is relatively higher when compared to other renewables. It is also noted that however crucial it is to have supportive government policy through effective strategy and schemes for enhanced biogas uptake, continuous support would form a vicious cycle for biogas sector. For instance, in Germany electricity sector, reduction of feed-in tariffs and cancellation of tax exemption would slow down biogas production (Lauer and Thrän, 2017). An optimal biogas plant extension is recommended to be orientated towards cost development of other flexibility developments.

One of the critical market barriers faced by biogas producers lies in the high price of biogas when compared to the relatively cheaper natural gas (Hoppe and Sanders, 2014). Fossil fuel is usually favoured over renewable fuels under the economic structure of many developing countries (Surendra et al., 2014). In some cases where biogas is used in the transport sector, the future of biogas depends on how competitors like bio-ethanol and electric vehicles develop (Ammenberg et al., 2018). Malaysia is currently on track with fuel subsidisation rationalisation for natural gas as government had approved revised natural gas tariff in order to bring natural gas price in Malaysia on par with international natural gas price by 2019, starting from 2015 (Gas Malaysia Berhad, 2017). Figure 6 shows the documentation structure of Third Party Access (TPA) for natural gas distribution pipeline under government effort to liberalise gas market as part of the 10th Malaysian Plan and the New Energy Policy (Energy Commission, 2017). Under a liberalised gas market, it is believed that with the right policy support, biomethane injection into the natural gas grid could be the next business opportunity for biogas investor to venture into innovative sustainable gas business. Rationalising subsidisation of fossil fuel does not necessarily mean that welfare of the people has to be compromised, especially during fuel price rises, it is advised that fiscal assistance could be introduced to the income-group that needed it most through a more targeted and transparent approach.

With that, value chain of renewable gas needs to be studied more throughout, especially with the participation of Standard and Industrial Research Institute of Malaysia (SIRIM) in order to ensure the composition of renewable gas injected into the grid does not jeopardise the natural gas quality and cause harmful effect to the pipeline infrastructure while ensuring a balanced supply and demand of gas market in Malaysia. Huang et al. (2016) conducted a study to investigate the challenges of integrating biogas into the natural gas distribution system. Wobbe number and combustion potential of mixed gas are used as indices for evaluation and concluded that biogas is able to complement energy shortages in China through conventional blending technologies.

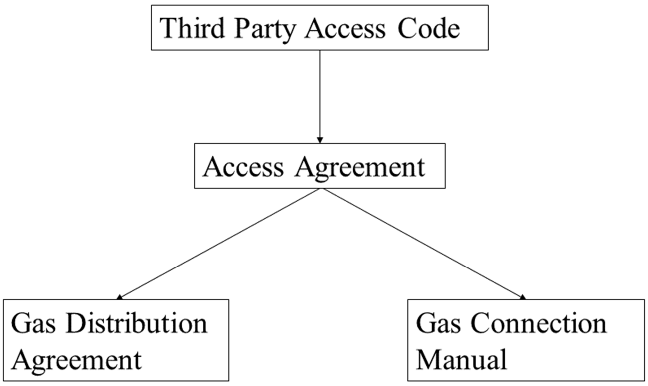

Figure 6 Documentation structure of TPA (Energy Commission, 2017)

Insufficient information on future development of energy policy is one of the challenges for investment in biogas plants (Purkus et al., 2018). A clear policies and support is important for the biogas industry to have confidence of a consistent commercial return of investment (Martin, 2015). Renewable energy market in Malaysia experienced a boom when Renewable Energy (RE) Policy 2010 was introduced (Hashim and Ho, 2011). Figure 7 presents the annual power generation of commissioned RE installations in MWh since RE Policy was introduced in 2010 (SEDA, 2018b). Biogas, as one of the potential renewable energy options, were identified with a potential 410 MW from POME to be installed by 2030 (Agensi Inovasi Maaysia, 2013).

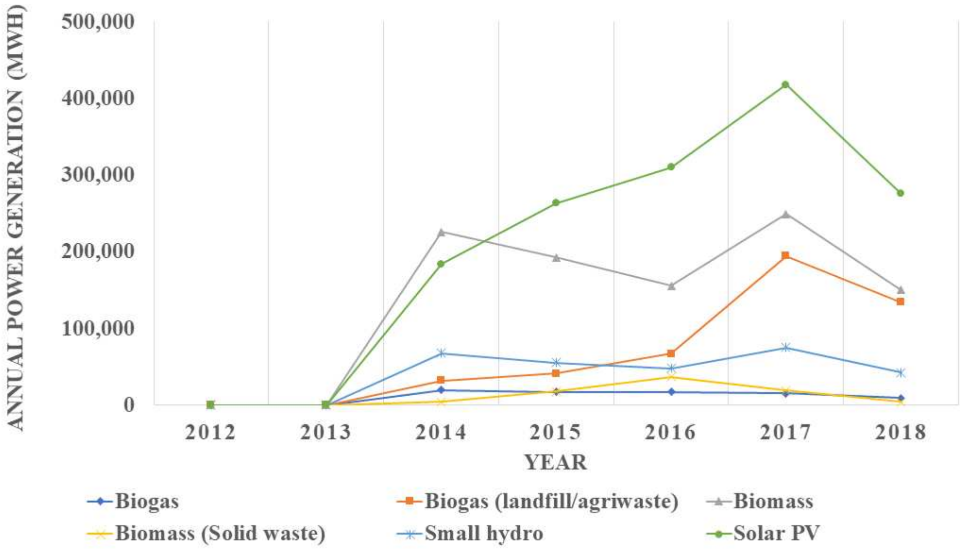

Figure 7 Annual power generation of commissioned RE installations (MWh) (SEDA, 2018c)

However, the latest cumulative capacity of installed biogas RE at 51.67 MW (SEDA, 2018c) shows that the potential of biogas is not fully utilised, not to mention other potential feedstocks, for instance, food waste, animal manures and industrial waste water treatment sludge have not been included in the estimation. The bottleneck of current biogas market in Malaysia is that there is lack of supportive policy tool to encourage further biogas uptake beyond power generation. The nature of biogas as RE is different from hydropower and solar PV as it relies on spatially scattered feedstocks, with relatively higher maintenance cost of the digester plant. Similar to the biomass RE, biogas RE requires a stable value chain to make the biogas market works, however, despite government's effort to nurture Malaysia's biomass industry through National Biomass Strategy 2020, biogas is more an option to optimise the biomass value chain than a bioenergy option by itself. Having said that, biogas is more commonly related as a waste management strategy under the solid waste management policies in Malaysia (Bong et al., 2017). However not all potential wastes are assessed as potential biogas feedstock. For instance, an experience of personal communications with actor from Biogas Association Malaysia (BAM) regarding the price of animal manure in the biogas market, it was responded that the market is 'young and open', the price is up to negotiation between the farmer and buyer. Uncertainties of future government support for biogas industry in the form of incentives, taxes demotivated biogas uptake (Ammenberg and Feiz, 2017). Such situations have illustrated how important it is to have market and price certainty to create confidence of a consistent return of investment in biogas investors, which eventually acts as a crucial factor to promote further biomethane utilisations through injection into the natural gas grid. Government involvement in the form of institutional support is thus essential for biogas uptake (Hoppe and Sanders, 2014).

Lack of R&D for locally fabricated AD is one of the barriers for biogas modernisation and development in developing countries. It is advised that more R&D efforts is needed to enhance biogas process, reduce cost of biogas technology and improve its affordability (Cheng et al., 2017). Lack of locally fabricated AD has caused the imported technology found unfit for local feedstock. For instance, food waste in Malaysia has higher fat content as compared to other countries which would require a biogas system that is suited to the characteristic of food waste composition. Higher fat content leads to higher volatile solid content, thus lower biogas generation (Bong et al., 2017). In addition, imported technology caused high investment cost of biogas deployment. Thus, it is suggested that research, development and commercialisation fund is needed from both government and industry partnership to promote deployment of locally fabricated AD technology. Moreover, locally fabricated anaerobic digester can also be customised to fit better into regionally available feedstock and local weather conditions that allow microbes to perform under optimal conditions.

Although government support in form Green Technology Financing Scheme (GTFS) has shown increased deployment of renewable energy technology, however biogas remains as a high-risk venture for financiers. This is mainly due to lack of technical knowledge regarding the nature of biogas plants among financing institution. Even after revised GTFS with addition of technical evaluation mechanisms, financing institution still remain reluctant to finance such high-risk venture (Zaharudin, 2016). There is also risk that public might protest for AD to be built near to their residential area (Bong et al., 2017) based on their negative perspective towards such technology. It is thus important for government and business player to organise and provide educational and awareness program for the non-technical people to be aware with current unsustainable practice of waste disposal and how anaerobic digester could be an economic and environmental feasible solution to the problem.

6. Conclusion

This paper investigated the role of policy instrument to facilitate upgrading of biogas to biomethane and injection of biomethane into the grid under the context of renewable energy policy in Malaysia. By estimating FiT tariff for biomethane injection through NPV approach, it is found that under current piped natural gas price, the proposed FiT (34.02 – 141.79 MYR/GJ) is economically incompetent for biomethane to be injected into the grid without government intervention in the form of policy and institutional support. However, natural gas price rationalisation may close the price gap, this is especially for biomethane derived from POME and food waste at 4 MW size. Among the four locally available feedstock assessed in this study, compare to pipeline transportation, POME and food waste show lower levelised cost, with lowest at 0.16 MYR/kWh and 0.14 MYR/kWh respectively under 4 MW size, 0.05 discount rate when transported by virtual pipeline, due to minimal competing utilisation value in addition to their higher biogas conversion rate.

High upfront of biogas plant construction, upgrading and injection facility which made up huge cost of the project indicated that with reduced investment cost, either through economic inventive, institutional enhancement and promotion of locally fabricated biogas technology through R&D could hugely reduce the LCOE of biomethane. As indicated from the LCOE of biogas, higher price of biogas in relative to lower natural gas price has form a market barrier for biogas to reach conventional consumption by public users. It is thus important for government to provide a clear policy landscape for biogas stakeholders to effectively commercialise and promote biogas energy to the consumers. Nevertheless, involvement of all biogas stakeholders, ranging from the private practitioner (biogas plant owner, technology transfer companies, producers, retailers), government authority and agencies, financial institution, academic institution (in the form of industrial-academic partnership for biogas technology R&D) are crucial for enhanced biogas uptake strategy that fits into the context of countries' renewable energy transition landscape.

It is advised that in future research, a more comprehensive analysis can be conducted to analyse how facilitating biomethane adoption can help achieve countries determined RE target by considering other renewable sources under the existing RE policy framework. A life cycle analysis could also be done to evaluate the sustainability criteria of biomethane produced from organic waste, as compared to natural gas. This could contribute towards certification of biomethane produced from organic waste source as renewable gas, thus can be sold at a premium price to industry or corporate consumers with high environmental awareness. Furthermore, the carbon mitigated from using biomethane as a renewable gas could be translated into a revenue stream for biomethane producer through a carbon market, thus addressing the economic barrier of utilising biogas as an energy source.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: