A SPATIAL-ECONOMIC OPTIMISATION OF WASTE TO BIOMETHANE IN MALAYSIA

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‘The world has enough for everyone’s needs, but not everyone’s greed.’

Mahatma Gandhi

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ABSTRACT

With ever growing population and demand for energy worldwide, the world is facing one of the most prominent issues of the century, environmental sustainability. The resources of the earth are nonetheless finite, the question is how can the limited resources be consumed in a more sustainable way? In the last decades, it has been observed that the energy sector is experiencing transition from fossil fuels to renewable sources, among which included biogas. Biogas is a type of bioenergy produced when organic matters are digested anaerobically. International Energy Agency (IEA) recently highlighted the diversity of benefits of biogas and anaerobic digester (AD) in the advent of circular economy in one of its report last year in 2018. The uniqueness of biogas as compared to other types of bioenergy lies in its production not only coming from energy crops, but also organic wastes. Despite being world second biggest palm oil producer, biogas (produced from palm oil mill effluent, POME) and AD are limitedly covered for its huge potential in Malaysia. Not to mention also the abundant availability of organic waste which could act as feedstock for AD. With raising concern on environmental pollution caused by the oil palm industry, biogas and AD could serve as an opportunity to reflect and showcase on sustainable planting of palm oil by taking massive adoption, but not merely a tag along option with renewable energy transition or waste management, as reflected in the current policy. Malaysian government has implemented Feed-in tariff mechanism since 2011 to promote the industry to adopt renewable energy (RE), which included biogas. However, lack of systematic planning of biogas supply chain, economic competitiveness of biogas and availability of infrastructure have become hindrance to harvest the benefits of biogas optimally. Thus, this study aims to explore potential of biogas upgrading to biomethane and the techno-economic feasibility of biomethane injection into the natural gas grid. An operational optimisation model, biomethane injection operational (BIOP) model was developed to study the relation between biomethane pressure, consumer demand and supply distance. It has found that in a supply distance of less than 50 km, most biomethane is supplied to industrial consumers despite having higher pressure requirement (20 psig), at the annual cost of 1.85 times higher than Business as Usual (BaU), due to high demand by industrial consumers. The study is then followed by an economic assessment to identify feasible FiT range for biomethane production from different feedstock, namely POME, food waste, cattle manure and chicken manure. The proposed FiT range, 59.79 – 147.82 MYR/GJ is economically incompetent for biomethane to compete in the energy market, unless there is government development plan to build distribution and injection infrastructure, which could bring down the cost significantly. Lastly, BeWhere ©, a spatial-techno-economic optimisation model was then adopted and extended to tackle the limitation of biogas utilisation due to location constraints. Optimised result shows that on-site biomethane plant using food waste as feedstock is the preferred configuration. Besides taking into account the environmental cost through carbon price (500 MYR/tCO_2), it has found that simultaneous rationalisation of natural gas subsidy (25 – 130 MYR/GJ) and attractive incentive for biomethane production (38 – 190 MYR/GJ) is required to make biomethane market competitive.

ABSTRAK

Akibat daripada peningkatan penduduk dunia dan penggunaan tenaga, salah satu isu yang paling menonjol pada abad ini adalah kemampanan alam sekitar. Sumber-sumber planet bumi adalah terhad, persoalannya ialah bagaimanakah sumber-sumber yang terhad ini dapat digunakan dengan cara yang lebih lestari? Dalam dekad yang lalu, sektor tenaga telah beralih dari sumber bahan api fosil kepada sumber yang boleh diperbaharui, antaranya termasuklah biogas. Biogas adalah sejenis biotenaga yang dihasilkan apabila bahan organik dicerna secara anaerobik. Agensi Tenaga Antarabangsa baru-baru ini telah menekankan kepelbagaian manfaat fermentasi anaerobik (AD) dan biogas untuk mencapai ekonomi sirkular dalam salah satu laporan pada tahun lepas, 2018. Keistimewaan biogas apabila berbanding dengan jenis biotenaga lain terletak pada pengeluarannya bukan sahaja berasal dari tanaman tenaga, tetapi juga berasal dari bahan buangan organik. Walaupun sebagai pengeluar minyak sawit kedua terbesar di dunia, potensi besar biogas dan AD (terutamanya hasilan daripada limbah cair pengolehan minyak sawit, POME) mendapat liputan terhad di Malaysia. Dengan peningkatan keprihatinan mengenai pencemaran alam sekitar yang disebabkan oleh industri kelapa sawit, penggunaan biogas dan AD boleh menjadi salah satu cara untuk manampilkan penanaman kelapa sawit yang lestari, tetapi bukan semata-mata pilihan sampingan sahaja bersama dengan dasar peralihan tenaga boleh diperbaharui ataupun dasar pengurusan sisa, seperti yang ditunjukkan dalam dasar sekarang. Kerajaan Malaysia telah melaksanakan mekanisme *Feed-in tariff* (FiT) sejak 2011 bagi menggalakkan industri untuk mengguna pakai tenaga boleh diperbaharui (RE), antaranya termasuk biogas. Walau bagaimanapun, kekurangan perancangan sistematik rantaian bekalan biogas, daya saing ekonomi biogas dan ketersediaan infrastruktur telah menjadi halangan untuk menuai manfaat biogas secara optimum. Oleh itu, kajian ini bertujuan untuk meninjau potensi penaik-tarafan biogas ke biometana dan kemungkinan suntikan biometana ke dalam grid gas asli dengan kajian tekno-ekonomi. Satu model pengoptimuman operasi, Model Operasi Suntikan Biometana dibangunkan untuk mengkaji hubungan antara tekanan biometana, permintaan pengguna dan jarak bekalan. Adalah didapati bahawa dalam jarak bekalan kurang dari 50 km, kebanyakan biometana dibekalkan kepada pengguna industri walaupun pengguna industri memerlu tekanan yang lebih tinggi (20 psig), dimana kos tahunannya adalah sebanyak 1.85 kali lebih tinggi daripada perniagaaan seperti biasa, situasi ini adalah disebabkan oleh permintaan yang tinggi daripada pengguna industri. Kajian ini kemudian diikuti dengan penilaian ekonomi untuk mengenalpasti jangkauan FiT untuk suntikan biometana hasilan bahan mentah yang berbeza, iaitu POME, sisa makanan, tahi lembu dan tahi ayam. Jangkaan FiT yang dicadangkan, 59.79 – 147.82 MYR/GJ adalah didapati terlalu mahal bagi biometana untuk bersaing di pasaran tenaga, kecuali jika terdapat rancangan pembangunan kerajaan yang boleh mengurangkan kos dengan ketara, antaranya termasuklah pembinaan infrastruktur agihan dan suntikan biometana. Akhir sekali, model pengoptimuman spatial-tekno-ekonomi, BeWhere © telah digunakan dan dibangunkan untuk menangani had penggunaan biogas akibat kekangan lokasi. Adalah didapati bahawa biometana *on-site* merupakan konfigurasi yang optimum di mana sisa makanan digunakan sebagai bahan mentahnya. Selain daripada mengambil kira kos alam sekitar melalui harga karbon (500 MYR/tCO_2), adalah didapati bahawa rasionalisasi subsidi gas asli (25 – 130 MYR/GJ) dan insentif biometana yang menarik (38 – 190 MYR/GJ) perlulah dilancarkan serentak bagi meningkatkan daya saing biometana dalam pasaran tenaga.

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LIST OF ABBREVIATIONS

3Rs	-	Reduce, reuse, recycle
ABC Plan	-	Action Plan for a Beautiful and Clean Malaysia
AD	-	Anaerobic digester
BAM	-	Biogas Association Malaysia
BaU	-	Business as Usual
Bio-CNG	-	Bio-Compressed Natural Gas
BIOP	-	Biomethane Injection Operational Model
BNM	-	Bank Negara Malaysia
CAD	-	Centralised Anaerobic Digestion
CAPEX	-	Capital expenditure
CBG	-	Compressed biogas
CBM	-	Compressed biomethane
CCS	-	Carbon capture and storage
CDM	-	Clean Development Mechanism
CER	-	Certified emission reductions
CHP	-	Combined heat and power plants
COD	-	Chemical-Oxygen Demand
COP 21	-	Paris Climate Change Conference
CPI	-	Consumer Price Index
DOE	-	Department of Environment
EUR	-	Euro
EUR ct	-	Euro cent
FiAHs	-	Feed-in Approval Holders
FiT	-	Feed-in Tariff
GAMS	-	General Algebraic Modelling System
GASCA	-	Gas System Cascading Analysis

GCPT	-	Gas Cost Pass Through
GDC	-	Gas demand coverage
GHG	-	Greenhouse gases
GHV	-	Gross heating value
GIS	-	Geographical Information System
GMB	-	Gas Malaysia Berhad
GTFS	-	Green Technology Financial Scheme
HGVs	-	Heavy goods vehicles
HHV	-	Higher heating value
IBR	-	Incentive Based Regulation
IEA	-	International Energy Agency
IF	-	Injection facility
IIASA	-	International Institute of Applied System Analysis
IRENA	-	International Renewable Energy Agency
IRR	-	Internal Rate of Return
JPSPN	-	National Solid Waste Management Department
KeTTHA	-	Ministry of Energy, Green Technology and Water
LBG	-	Liquefied biogas
LBM	-	Liquified biomethane
LCOG	-	Levelised cost of gas
LNG	-	Liquefied natural gas
MESTECC	-	Ministry of Energy, Science, Technology, Environment and Climate Change
MaCGDI	-	Malaysia Centre for Geospatial Data Infrastructure
MHLG	-	Ministry of Housing and Local Government
MILP	-	Mixed Integer Linear Programming
MINLP	-	Mixed Integer Non Linear Programming
MIPV	-	Malaysia Building Integrated Photovoltaic Technology Application Project
MSW	-	Municipal solid waste

MYR	-	Malaysian Ringgit
NASA	-	National Aeronautics and Space Administration
NG	-	Natural gas
NLP	-	Non-Linear Programming
NPV	-	Net Present Value
NSP	-	National Strategic Plan
NSWMB	-	National Solid Waste Management Department
OD	-	Origin Destination
OLR	-	Organic loading rate
OM	-	Operational and maintenance
OPF	-	Oil palm frond
OPT	-	Oil palm trunk
OSM	-	Open Street Map
POME	-	Palm oil mill effluent
PPSPPA	-	Solid Waste Management and Public Cleansing Corporation
PSA	-	Pressure swing absorption
PV	-	photovoltaic
RE	-	Renewable energy
REBF	-	Renewable Energy Business Fund
RG	-	Renewable gas
ROA	-	Real options analysis
ROI	-	Return of investment
SCEA	-	Supply Chain Economic Assessment
SEDA	-	Sustainable Energy Development Authority
SIRIM	-	Science and Industrial Research Institute of Malaysia
SREP	-	Small Renewable Energy Power Program
SSF	-	Seasonal Swing Factor
SWCorp	-	Solid Waste and Public Cleansing Management Corporation

SWM	-	Solid waste management
TBPA	-	Time-Based Pinch Analysis
TFI	-	Tropical Future Initiative
TNB	-	Tenaga Nasional Berhad
TOC	-	Trace Organic Components
TPA	-	Third Party Assess
UK	-	United Kingdom
UNFCCC	-	United Nations Framework Convention on Climate Change
USD	-	United State Dollar
VS	-	Volatile solid
WM-MP	-	Waste Minimisation Master Plan
WtE	-	Waste-to-energy

LIST OF SYMBOLS

A	-	amortised factor
$AB_{s,rm}$	-	available biomass at supply *s* (PJ/y)
$b_{s,rm,p,tech,size}$	-	amount of feedstock transported for plant *p* at technology *tech* and size *size* (PJ/y)
bar	-	bar (pressure unit)
c	-	capcity
$C(IP)$	-	gas consumption flowrate (m^3/h)
$CAPEX$	-	anticipated project lifetime (y)
$CAPEX_{AD}$	-	Capital cost of anaerobic digester (MYR/kW)
$CAPEX_{Com}$	-	Capital cost of compressor (MYR)
$CAPEX_{IF}$	-	Capital cost of injection facility (MYR/kW)
$CAPEX_{P}$	-	Capital cost of stainless steel pipeline (8-in diameter) (MYR/km)
$CAPEX_{Up}$	-	Capital cost of upgrader (MYR/(m^3/h biogas))
$CAPEX_{VP}$	-	Capital cost of virtual pipeline (MYR)
Cap_{PLANT}	-	Plant capital cost (MMYR/y)
$Carbon\ price$	-	Proposed carbon price (MMYR/tCO_2)
$Cost$	-	Cost of biomethane production and injection (MMYR/y)
$CostM$	-	pipe material cost (MYR/t)
$Cost_{Adm}$	-	Administrative cost (MYR)
$Cost_{Con}$	-	Construction cost (MYR)
$Cost_{digestateSP}$	-	Digestate closed storage cost (MYR)
$Cost_{F}$	-	Fuel cost (MYR/L)
$Cost_{FEEDS}$	-	Feedstock cost (MMYR/y)
$Cost_{feedstockSP}$	-	Feedstock storage and preparation cost (MYR)
$Cost_{Ins}$	-	Installation cost (MYR)

$Cost_{Mis}$	-	Miscellaneous cost which included digestate handling cost, labour cost, services, insurance, taxes, pH control and biogas cleaning (MYR/y)
$Cost_{NG}$	-	Natural gas cost (MMYR/y)
$Cost_{T}$	-	Transmission cost (MYR/kWh)
$CpCom$	-	compressor capital cost (MYR)
$CpPipe$	-	pipeline capital cost (MYR)
$CpUpgrade$	-	upgrader capital cost (MYR)
d	-	pipe inside diameter (mm)
d	-	Day
D	-	Transportation distance (km)
D	-	pipe outside diameter (mm)
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)
$Emission$	-	Total carbon emissions of biomethane production and injection (tCO_2/y)
$Emiss_{NG}$	-	Carbon emissions from natural gas burning (tCO_2/y)
$E_{balanceAD}$	-	Energy balance of an AD system
$E_{methane}$	-	Methane gross energy content
E_{nutr}	-	Nutrient energy content
E_{water}	-	Water energy content
E_{OM}	-	Energy content of digestate organic content
E_{log}	-	Logistic energy used
E_{pret}	-	Pre-treatment energy used
$E_{dig.op}$	-	Digester energy used
$E_{biog.post}$	-	Biogas post-treatment energy used
$E_{dig.post}$	-	Digestate post-treatment energy used
E_{add}	-	Chemical additives energy content

E_{inf}	-	AD maintenance energy used
f	-	feedstock
f	-	friction factor, dimensionless
FC	-	Fuel consumption (L/km)
G	-	index for gas supply
G	-	gas gravity (air = 1.00)
GJ	-	Gigajoule
H	-	Operating hours
h	-	Hour
in	-	Inch
IP	-	index for demand area
K	-	Kelvin
kcal	-	Kilocalories
K_f	-	Constant based on type of flow equation
kPa	-	Kilopascal
kW	-	Kilowatt
L	-	length of pipe (km)
M_f	-	Feedstock equivalent
mi	-	Mile
MJ	-	Megajoule
mm	-	Millimetre
Mm^3	-	million cubic meter
MMBTU	-	million British Thermal Unit
MMYR	-	Million Malaysian Ringgit
Mpa	-	Megapascal
MW	-	Megawatt
MWh	-	Megawatt
n	-	Flow exponent based on type of flow equation
$NGPrice$	-	natural gas price (MYR/m^3)

NoT	-	Number of trips per year
$OMCom$	-	operating and maintenance cost of compressor (MYR)
$OMPipe$	-	operating and maintenance cost of piping infrastructure (MYR)
OM_{PLANT}	-	Biomethane production and injection cost (MMYR/y)
$OMUpgrade$	-	operating and maintenance cost of uograder (MYR)
$OPEX$	-	Total operational and maintenance cost (MYR/y)
$OPEX_{AD}$	-	Operational cost of anaerobic digester (MYR/kW)
$OPEX_{Com}$	-	Operational cost of compressor (MYR/kWh)
$OPEX_{IF}$	-	Operational cost of injection facility (MYR/kW)
$OPEX_{P}$	-	Operational cost of pipeline (MYR/km)
$OPEX_{Up}$	-	Operational cost of upgrader (MYR/(m^3/h biogas)
$OPEX_{VP}$	-	Operational cost of virtual pipeline (m3/trip)
Pa	-	Pascal
$PE_{p,tech}$	-	plant efficiency of each plant *p* and tech *tech*
PMC	-	pipe material cost (MYR)
POF	-	Plant operating factor
$Power$	-	compression power (kW)
ppm	-	part per million
$Production$	-	Biomethane production of plant (GJ)
psig	-	Pound-force per square inch (gauge)
P_1	-	upstream pressure of pipeline (kPa)
P_2	-	downstream pressure of pipeline (kPa)
P_b	-	base pressure (kPa)
P_d	-	discharge pressure of gas (kPa)
P_s	-	suction pressure of gas (kPa)
Q	-	gas flow rate (m^3/d)
r	-	Feed-in Tariff (MYR/GJ)
Rev_{BIOME}	-	Revenue generated from biomethane selling (MMYR/y)

$S(G)$	-	gas supply (m^3/h)
sm^3	-	standard cubic meter
$SS_{s,rm}$	-	supply share at supply s
t	-	discount rate (%)
t	-	Tonne
T	-	pipe wall thickness (mm)
TJ	-	Terajoule
$TotCAPEX_P$	-	Total CAPEX of biomethane transported via pipeline (MYR)
$TotCAPEX_T$	-	Total CAPEX of biomethane transported via distributor (MYR)
$TotCAPEX_{VP}$	-	Total CAPEX of biomethane transported via virtual pipeline (MYR)
$TotCost$	-	total cost (MYR/y)
$TotOPEX_P$	-	Total CAPEX of biomethane transported via pipeline (MYR/y)
$TotOPEX_T$	-	Total CAPEX of biomethane transported via distributor (MYR/y)
$TotOPEX_{VP}$	-	Total CAPEX of biomethane transported via virtual pipeline (MYR/y)
$TransCost_{BIOME}$	-	Biomethane transportation cost (MMYR/y)
$TransCost_{FEEDS}$	-	Feedstock transportation cost (MMYR/y)
$TransEmiss_{FEEDS}$	-	Carbon emissions from feedstock transportation (tCO_2/y)
$TransEmiss_{BIOME}$	-	Carbon emissions from biomethane transportation (tCO_2/y)
T_1	-	suction temperature of gas (K)
T_b	-	base temperature [K (273 + °C)]
T_f	-	average gas flowing temperature [K (273 + °C)]
$u_{p,tech,size}$	-	binary operation to indicate whether a plant a set up at plant location p
V_{BG}	-	Biogas volumetric flowrate (m^3/h)
V_{BM}	-	Biomethane volumetric flowrate (m^3/h)

$x_{p,tech,size}^{BP}$	-	amount of biomethane produced at each plant p at tech *tech* and size *size* (PJ/y)
$x_{p,tech,size}^{BE}$	-	amount of excess biomethane produced at each plant p at tech *tech* and size *size* (PJ/y)
$x_{p,tech,size,g}^{BU}$	-	amount of biomethane used for injection at gas station *g* (PJ/y)
$x_{c,g}^{consumption}$	-	amount of gas consumption at gas station *g* (PJ/y)
x_{g}^{NG}	-	amount of natural gas used to fulfil demand at gas station g (PJ/y)
y	-	Year
Z	-	gas compressibility factor at the flowing temperature in pipe, dimensionless
Z_1	-	compressibility of gas at suction conditions of compressor, dimensionless
Z_2	-	compressibility of gas at discharge conditions of compressor, dimensionless
ɤ	-	ratio of specific heat of gas, dimensionless
η_a	-	compressor adiabatic (isentropic) efficiency, decimal value
ºC	-	degree Celcius
°F	-	Fahrenheit

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Biomethane, which resorted the characteristic of natural gas for its high methane composition (84 – 99 %) is an emerging energy option (Sun et al., 2015). Biomethane is also known as upgraded biogas / landfill gas, renewable gas, or green gas. Biomethane is commonly upgraded from biogas produced from anaerobic digestion (AD) or obtained from a combination of biomass gasification and methanation process. AD is a biological process where large organic matters are broken down into small molecules by microbes in the absence of oxygen (Mao et al., 2015). Gasification, on the other hand, is a process where solid biomass is converted into gases (carbon dioxide, hydrogen and carbon monoxide) under high temperature (> 700 ˚C)(Li et al., 2015). Both technologies, anaerobic digestion and gasification, are popular methods used in treating biomass waste while producing renewable energy. In this thesis, biomethane is referred as upgraded biogas from AD process as AD is economically more feasible for practical implementation in countries with high moisture content organic waste. This chapter consists of seven sections: Section 1.2 will present the history and background of biomethane development as an emerging energy options; Section 1.3 will discuss the challenges and problems faced by biomethane development due to the complexity when AD is treated as a waste management strategy, in another words, waste-to-energy (WtE). Following that, Section 1.4 will present research objectives while Section 1.5 will discuss the scopes for the development of a novel spatial-economic framework of biomethane supply system planning. At last, the importance of this study and its contribution towards Malaysia will be discussed in Section 1.6.

1.2 Research Background

Methane is a double-edged sword, it can benefit human as an energy source, but it can also be harmful to the environment when it is released into the atmosphere. In year 2013, National Aeronautics and Space Administration (NASA) reported that the carbon dioxide concentration in the air has increased to more than 400 ppm for the first time (Laurie, 2017). Burning of fossil fuels for power generation, industrial activities and transportation are the main contributors of greenhouse gases (GHG) emissions into the air. This alarming situation has triggered nations' commitment to maintain global average temperature to below 2 ˚C increment before the pre-industrial level, as ratified in Paris Agreement. There are 176 ratified Parties (out of 197) by May 2018 (UNFCCC, 2015). Several actions have been carried out, those included adoption of new technology like carbon capture and storage (CCS), transition to renewable energy, formulation of climate policy and removal of fossil fuels subsidies.

Besides carbon dioxide, methane, which accounted for about 16 % of the GHG in the atmosphere globally (Edenhofer et al., 2014), is 25 times more harmful to the environment than carbon dioxide (Global Warming Potential for 100-y = 25) (EPA, 2018). Methane can be naturally found in biogas released from organic matters in the absence of oxygen. Biogas from palm oil mill effluent (POME) usually contains 60 - 70 % of methane (Loh & Choo, 2013) while landfill gas usually contains 50 - 60 % of methane (Abushammala et al., 2009). When biogas is left untreated and escaped into the atmosphere, it become a severe contributor towards global warming. Therefore, it is important to capture biogas from releasing into the atmosphere, furthermore, captured biogas can then be utilised as an alternative energy option, making it the best epitome of killing two birds with one stone.

1.2.1 From Biogas to Biomethane

This section discusses the biogas development emerges over the years. The idea of biogas has long been recognised as a flammable fuel released from rotten vegetables since the ancient Persians time. The first modern biogas plant could be dated back to 1859, when the sewage stabilisation facility was built in Bombay, India (Kingdom of BioEnergy, 2017). The idea is then brought to the UK in 1895 and later established to become a more organised biogas system in UK and Germany during early 1900s. The utilisation of biogas was more commonly seen in rural farming villages in India, China and Nepal during 1960s (Bond & Templeton, 2011). With the abundance of animal manures, biogas generated were used as fuel for cooking and heating purposes (Kingdom of BioEnergy, 2017). Until recently, for the past 40 years in Europe and North America, biogas development has advanced to a larger and more complex scale, with higher efficiency and specification for power generation, transportation and industrial usage (Wellinger et al., 2013). Biogas development is described as setting up dedicated biogas facilities which the process can be controlled and optimised with established business prospective. In another words, harnessing the nature potential to produce commercially viable renewable biofuel (Wellinger et al., 2013). Many biogas cleaning, conditioning and upgrading technologies have also been introduced to enhance the fuel quality of biogas, yielding biomethane which has the methane composition that is comparable to that of the natural gas, opening door for biomethane injection into natural gas grid for larger utilisation purposes. Further explanation of different biogas / biomethane utilisations will be discussed in Chapter 2.

Today in the 21st century, environmental concern has become the motivation of growing commitment for biogas development globally, for it is able to reduce GHG emissions into the air while reducing environmental pollution impacts from waste disposal. Biogas / biomethane is also a potential renewable energy source, thus making it a recognised solution towards cleaner energy and more sustainable waste management solution for policy makers.

1.2.2 Biogas Development in Malaysia

Malaysia, as a tropical country with abundance organic waste and biomass resources from the agricultural industry, has huge potential for biogas development. Over the years, biogas development in Malaysia has been driven by renewable energy

(RE) adoption and solid waste management (SWM) development. This section will describe biogas development of this country from these two perspectives.

1.2.2.1 Renewable Energy Development

On year 2001, Fifth Fuel Policy was launched under the 8th Malaysian Plan (2001 – 2005) in looking alternative energy solutions to address challenges relating to fluctuating oil price, depleting fossil fuels resources and increasing climate concern due to burning of fossil fuels. Under this policy, Malaysia target to achieve 5 % of its power generation from renewable sources, that is 500 MW out of 20,000 MW of generation capacity (Maulud & Saidi, 2012). However, the target has failed miserably due to unattractive economic return (an Internal Rate of Return (IRR) of 6 – 8 % only under RM 0.17 per kWh of electrical tariff purchase by monopolistic utility company in the country), coupled with sluggish global financial growth due to Asian Financial Crisis (1997) and lack of cross ministry jurisdiction backed by legislation for effective implementation (Maulud & Saidi, 2012). Although the target was again set in 9th Malaysian Plan (2006 – 2010), only 41.9 MW of RE generation (< 1.0 %) was achieved by 2009, utilising landfill gas and empty fruit brunch from oil palm plantation.

The penetration of RE only started to see positive growth when Renewable Energy Act was enforced in 2011, where numerous economic incentives, for instance, Feed-in Tariff (FiT) mechanisms, Green Technology Financial Scheme (GTFS) and RE business fund were introduced to improve economic competitiveness of RE as compared to the highly subsidised fossil fuels (Hashim & Ho, 2011). Sustainable Energy Development Authority (SEDA) was established under the Ministry of Energy, Green Technology and Water (KeTTHA) to ensure successful implementation of the policy. Those RE included biomass energy, biogas, mini-hydro, solar energy and solid waste converted energy. Among all these potential RE, biogas is also considered as one of the potential renewable energy as it has high potential from the country's agricultural activities and organic waste generation.

Table 1.1 shows the proposed FiT for electricity generated from biogas. The potential of biogas generated electricity was estimated to be 100 MW by 2015 (Bong et al., 2017), with a reserve of 410 MW by 2030 (Khor & Lalchand, 2014). Despite having huge potential, only 6.48 MW and 51.76 MW of biogas capacity is installed utilising landfill and feedstock from agricultural waste by 2017 (SEDA, 2018b).

Table 1.1 FiT rate for electricity produced from biogas (SEDA, 2018a)

Capacities	**Years**	**FiT rate (MYR/kWh)**	**Degression rate (%)**
< 4 MW	16	0.32	0.5
> 4 MW < 10 MW	16	0.30	0.5
> 10 MW < 30 MW	16	0.28	0.5
Bonus for gas engine > 40 % efficiency	16	0.02	0.5
Bonus for local manufacturer	16	0.05	0.5
Bonus for landfill or sewage gas	16	0.08	0.5

1.2.2.2 Waste Management Development

It is obvious that biogas electricity in Malaysia is more commonly seen as energy converted from waste like biogas from palm oil mill effluent (POME) and landfill gas. Being the world second largest palm oil exporter after Indonesia (Shuit et al., 2009), with more than 5.74 million hectares of plantation, Malaysia's oil palm industry accounts to 36.75 % of world palm oil production (MPOC, 2016). Ponding system remained the main treatment towards the organic-contents-rich POME before anaerobic treatment was introduced. Ponding system was not encouraged due to the degradation process requires high retention time, biogas released into the atmosphere was not controlled, thus causing environmental problem, not to mention that global warming potential of methane is 25 times that of CO_2 (Gardner et al., 1993). It is estimated that biogas from POME consisted of 54.4 % of CH_4, or, 1.5 L/min/m^2 biogas flow rate (Yacob et a., 2006). When Clean Development Mechanism (CDM) was introduced under Kyoto protocol in 1997, it triggered POME treatment from ponding system to anaerobic digestion. There were 36 biogas recovery projects registered by

September 2012. Biogas recovered not only can be utilised for power generation, CDM allows palm oil millers to earn extra revenue by recovering biogas. Based on carbon credit price of 43 MYR/t CO_2e (Yoshizaki et al., 2012), each mill can potentially earn an extra revenue of 600,000 MYR to 3 million MYR per year, depending on size of certified emission reductions (CER).

Other than capturing biogas from POME digestion, landfill site operators also tapped into CDM by proposing gas utilisation systems to be installed in landfill sites. In Malaysia, 95 % of collected MSW is disposed in landfill (Johari et al., 2014). As of 2010, there were 310,000 m^3 CH_4 emitted into the atmosphere, it is estimated that the emission will increase to 370,000 m^3 by 2020 (Johari et al., 2012). Landfill gas recovery becomes a prominence action to take. However, there were only 15 sanitary landfill sites out of 162 landfill sites in Malaysia, not to mention landfill gas is contributing 47 % of CH_4 emissions in Malaysia (Tan et al., 2014a).

1.3 Problem Statement

Although economic incentives and policy support shown to be the driver of RE adoption in Malaysia, unlike other RE, biogas development faces some challenges due to technical and logistic planning complexity as it involves the utilisation of scattered waste generation as feedstock supply. Other than being recognised as a technology to handle organic waste and mitigate GHG emissions, there is lack of a systematic approach dedicated for optimal biogas development.

1. Not all possible biogas utilisation pathways are being explored in the Malaysian context even though it is maturely adopted in other countries. As studied in the background, palm oil mills and landfill sites show increasing biogas capture when CDM mechanism was introduced. Captured biogas is further utilised for power generation when the government introduced the FiT mechanism. Some palm oil millers utilised excess biogas by upgrading biogas to fuel trucks for transportation purpose (Loh et al., 2017). The possibility of biomethane injection into the natural

gas grid, thus connecting the biogas market to the bigger conventional gas market remained unexplored.

2. The utilisation of biogas for power generation and feed into the grid is constrained by spatial limitations. It is learnt from previous experiences that palm oil mills and landfill sites located too far away from the electricity grid (usually more than 10 km) are left considered economically infeasible and technically ineffective for feed in, while there is no electricity demand nearby the production plant. There is an absence of systematic planning involving economic, technical and spatial aspects to integrate location-dependent-RE into the centralised utility system. Therefore, it is important to consider spatial availability of supply and demand during RE planning.

3. The current RE policy and economic incentives in Malaysia are insufficient for optimal biogas utilisation as biogas is limited to power generations only while this renewable source can perform more than that when connected to the centralised gas grid. Biogas also shows relatively slower growth under the FiT mechanism when compared to other RE like solar, not to mention that the incentives are only effective for a limited period of time (16 years for biomass and biogas). Other possible financing mechanisms and incentives dedicated for biomethane injection into the natural gas grid are not examined.

Based on the biogas development problems described above, a few research questions are raised:

1. What is the technical and economic feasibility of the injection of biomethane injection into the natural gas grid using biogas generated from waste?
2. How can the spatial limitation of connecting RE to centralised utility system be handled in a systematic approach?
3. What is the level of policy support required in order to promote biomethane injection into the centralised gas grid, especially in a fossil-fuel heavily dependent country?

1.4 Research Objectives

In order to address the above research questions, this research aims to develop a systematic framework for biomethane injection into the grid:

1. To develop an optimisation model that is pressure dependent in order to study and identify optimal scenario for biomethane injection into natural gas grid by considering pressure, distance and demand of different users: industrial, commercial and residential users.

2. To extend a spatial-economic optimisation model of waste to biogas generation. This model aims to minimise the total cost of biogas supply chain by considering feedstock availability, gas demand, transportation cost, capital cost of different biomethane generation capacity and distribution mode. The spatial-economic model should be able to:
   i. Identify the optimal biogas production to meet a targeted biogas demand;
   ii. Determine the optimal capacity and locations of biogas plants based on different scenarios.

3. To examine policy and economic framework that will improve biogas market in a highly competitive energy market by identifying the underlying policy and regulatory issues related to the development of biogas sector. The suggestion will be based on the sensitivity analysis of the developed costing model and spatial-economic optimization model where it can identify:
   i. Feed-in-tariff of upgraded biogas into natural gas grid;
   ii. Financing mechanisms for the construction of biogas plants and infrastructure.

1.5 Research Scope

Based on the intended research objectives, the scopes of the study are identified as below:

1. Conducting a thorough literature review on:
   i. Current Malaysia RE and SWM policy development background that are related to biogas;
   ii. Overview of biogas supply chain from potential biogas feedstock to different potential biogas utilisation with distribution methods;
   iii. Research state-of-art on biomethane transportation through pipeline;
   iv. Research state-of-art on systematic planning and optimisation of biomethane supply chain;
   v. Current trend of biomethane FiT mechanism globally.

2. Developing operational model that studies the economic and technical feasibility of biomethane injection into the natural gas grid through pipeline. The specific scopes are:
   i. Developing an Biomethane Injection Operational Model (BIOP) to identify the best scenario (residential, commercial or industrial) for biomethane injection;
   ii. Conducting a case study, namely Seelong Sanitary Landfill Site with sensitivity analysis to assess the trade-off between pressure and demand of biomethane transportation through pipeline to different gas consumers.

3. Adopting and adapting BeWhere © model (Leduc, 2009), a spatial-techno economic optimisation model to identify the optimal biogas production, plant capacity and location in Malaysia context. The specific scopes are:
   i. Gathering spatial explicit data on the availability of feedstock supply, cost of bio processing technology, energy demand and transportation network of Johor region;

ii. Conducting sensitivity analysis based on different level of subsidy rationalization of natural gas, different biomethane price and different carbon price.

4. Developing Supply Chain Economic Assessment (SCEA) model to identify the optimal FiT rate for biomethane injection into the natural gas grid. The specific scopes include:
   i. Identifying the initial FiT based on Net Present Value (NPV) calculation;
   ii. Performing sensitivity analysis based on varying distances and plant capacities to evaluate its profitability from business perspective.

1.6 Significance of Study

Through answering the above described research objectives and addressing all the research scopes, this research contributes to the growth of a mature biogas market in Malaysia through the structural and systematic optimisation models. The details of the significance of the research are described below:

1. This research contributes to the research state-of-art on biomethane transportation through pipeline. The new model BIOP evaluates the trade-off between pressure and demand when evaluating biomethane injection technical and economic feasibility into the gas grid.

2. The extended BeWhere © model (Leduc, 2009) marked the first model that is successfully implemented in Malaysia for renewable energy resources planning from the International Institute of Applied System Analysis (IIASA). It opens opportunities for the model to be further applied to the whole Malaysia, or even South East Asian countries through the ongoing Tropical Future Initiative (TFI).

3. The proposed research is aligned to the 11th Malaysian Plan 2016 – 2020 (2015) on increasing share of renewable energy in the country's power generation to 11% by 2020. The SCEA model will assist policy makers to further explore biogas

utilisation as an renewable energy through injection into the centralised natural gas grid, specifically in the context of fossil fuel heavily dependent Malaysia.

Publications contributing to this research can also be found in List of Publications section.

1.7 Thesis Outline

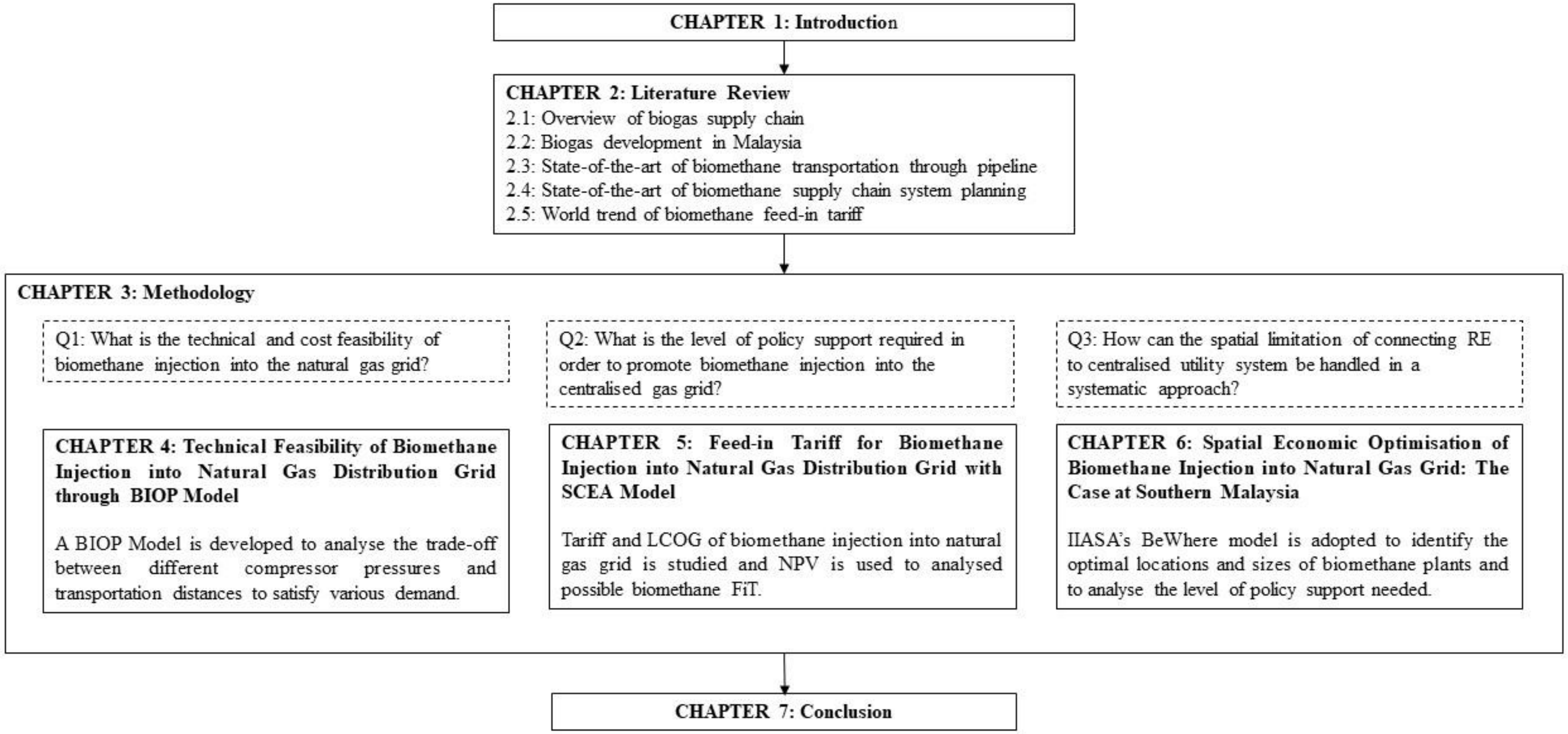

Figure 1.1 Thesis outline

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