SUPPLY CHAIN OPTIMIZATION OF PALM OIL MILL EFFLUENT TO BIOCOMPRESSED NATURAL GAS FOR INDUSTRIAL USAGE

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ABSTRACT

Virtual distribution of Biocompressed Natural Gas (BioCNG) is economically attractive to industries which are remotely located from natural gas pipeline. However, this concept poses some issues concerning logistics due to scattered spatial distribution of palm oil mills. Addressing these aspects requires an integrated spatial planning and optimization to synthesise location and allocate network of BioCNG virtual transportation to the respective industry. This study presented the development of integrated spatial planning and optimization of BioCNG supply and distribution network through virtual pipeline to meet on-site energy demand of specific industry. This study also aimed to investigate the contribution of optimized BioCNG supply chain towards systematic energy hub among other energy alternatives. The data from network analysis of aeronautical reconnaissance coverage geographic information system were coded into generalized algebraic modelling system and advanced interactive multidimensional modelling system modelling to generate supply cost curve for multiple source of energy carrier i.e. liquefied natural gas import, natural gas (NG) through pipeline network, and BioCNG supply chain through virtual pipeline. The results show that standardised optimum compression pressures of BioCNG without and with biogas upgrading are 53.8 bar and 215 bar respectively. Minimum total cost per energy of decentralised BioCNG supply chain is 3.57 USD/GJ while that of centralised BioCNG supply chain is 3.64 USD/GJ. Decentralised production pathway was found to be more economically effective compared to centralised production at the study area of Johor. To achieve a 20 % greenhouse gas (GHG) emission reduction, energy mix with a combination of NG from natural gas grid extension, BioCNG production with upgrading and coal is required for the demand locations considered. BioCNG production with upgrading is a cost effective mitigation method on GHG emission reduction. The optimum energy mix not only has lower emission level than baseline but also reduces the total energy supply cost by 19.1 %.

ABSTRAK

Pengedaran Bio-gas asli termampat (BioCNG) melalui talian paip maya mempunyai manfaat ekonomi terutamanya untuk industri-industri yang terletak jauh dari talian paip gas asli. Namun, konsep ini menimbulkan isu-isu pengedaran disebabkan lokasi-lokasi kilang minyak kelapa sawit yang bertaburan. Untuk menangani aspek-aspek ini, kaedah kolerasi antara perancangan rangkaian pengedaran dan pemodelan pengoptimuman perlu dibuat untuk menghasilkan keputusan lokasi dan menentukan peruntukan untuk rangkaian pengedaran BioCNG melalui talian paip maya ke industri tertentu. Kajian ini menyampaikan pembangunan kaedah kolerasi antara perancangan rangkaian pengedaran dan pemodelan pengoptimuman untuk rangkaian bekalan dan pengedaran BioCNG melalui talian paip maya untuk memenuhi permintaan tenaga di lokasi masing-masing untuk industri tertentu. Kajian ini juga bertujuan untuk menyiasat sumbangan rantaian bekalan BioCNG yang optimum kepada interaksi sumber-sumber tenaga yang sistematik antara jenis-jenis tenaga lain. Data yang diperoleh daripada analisis rangkaian dengan menggunakan sistem maklumat geografi liputan peninjauan aeronautika telah dikodkan kepada sistem pemodelan algebra umum dan sistem pemodelan multidimensi interaktif lanjutan untuk mendapatkan keluk-keluk kos sumber tenaga untuk pelbagai sumber tenaga seperti pengimportan gas asli cecair, gas asli (NG) melalui rangkaian talian paip dan BioCNG melalui talian paip maya. Keputusan menunjukkan bahawa tekanan mampatan yang seragam dan optimum untuk BioCNG tanpa dinaiktaraf ialah 53.8 bar dan untuk BioCNG dinaiktaraf ialah 215 bar. Kos keseluruhan terendah per tenaga untuk pengeluaran BioCNG tidak berpusat ialah 3.57 USD/GJ dan pengeluaran BioCNG berpusat ialah 3.64 USD/GJ. Pengeluaran BioCNG tidak berpusat didapati lebih efektif dari segi ekonomi berbanding dengan pengeluaran BioCNG berpusat untuk kawasan kajian di Johor. Untuk mencapai 20 % pengurangan pelepasan gas rumah hijau (GHG), komposisi tenaga yang optimum terdiri daripada NG melalui sambungan grid gas asli, BioCNG dinaiktaraf dan arang batu diperlukan untuk lokasi-lokasi permintaan yang dipertimbangkan. BioCNG dinaiktaraf berkesan untuk mengurangkan pelepasan GHG dari segi kos. Komposisi tenaga yang optimum ini bukan sahaja mengurangkan pelepasan GHG tetapi juga mengurangkan jumlah kos sumber tenaga dengan 19.1 % pengurangan.

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LIST OF ABBREVIATIONS

AD	-	Anaerobic Digestion
AFBR	-	Anaerobic fluidized bed reactor
AIMMS	-	Advanced Interactive Multidimensional Modelling System
ArcGIS	-	Aeronautical Reconnaissance Coverage Geographic Information System
ASEAN	-	Association of South East Asian Nations
BioCNG	-	Biocompressed natural gas
bio-SNG	-	Biomass based synthetic natural gas
BND	-	BioCNG Network Design
BOD	-	Biochemical oxygen demand
BVPO	-	BioCNG Virtual Pipeline Operational
CAPEX	-	Capital expenditure
CHEMS	-	Chemical scrubbing
CHP	-	Combined heat and power
CIGRE	-	International Council on Large Electric System
CLB	-	Covered lagoon biodigester
CMN	-	Carbon management network
CNG	-	Compressed natural gas
COD	-	Chemical oxygen demand
CPO	-	Crude palm oil
CSTR	-	Continuous stirred tank reactor
CWN	-	Chilled water network
DEG	-	Distributed energy generation
DER	-	Distributed energy resources
EAEEA	-	Energy Alternatives Economic and Emission Assessment
ECI	-	Emission reduction to cost increase ratio
ECD	-	Emission reduction with cost decrease value
EIA	-	Energy Information Administration
EFB	-	Empty fruit bunch
ESCA	-	Electric System Cascade Analysis

ESRI	-	Environmental Systems Research Institute
ETRC SIRIM	-	Environmental Technology Research Centre of Standard and Industrial Research Institute of Malaysia
FiT	-	Feed-in-tariff
FFB	-	Fresh fruit bunches
GAMS	-	Generalized Algebraic Modelling System
GDP	-	Gross Domestic Product
GHG	-	Greenhouse gas
GIS	-	Geographical information systems
GPSA	-	Gas Processors Suppliers Association
HEN	-	Heat exchanger network
HRT	-	Hydraulic retention time
IEA	-	International Energy Agency
KeTTHA	-	Ministry of Energy, Green Technology and Water
LCA	-	Life-cycle assessment
LIP	-	Linear integer programing
LNG	-	Liquefied natural gas
LP	-	Linear programming
LSS	-	Large-scale solar
MaCGDI	-	Malaysia Centre for Geospatial Data Infrastructure
MCDM	-	Multi-Criteria Decision Making
MEMS	-	Membrane separation
MILP	-	Mixed-integer linear programming
MINLP	-	Mixed-integer nonlinear programing
MSW	-	Municipal solid waste
NEM	-	Net energy metering
NG	-	Natural gas
NGV	-	Natural gas vehicle
NLP	-	Non-linear Programming
OLR	-	Organic loading rate
OPEX	-	Operating expenditure
PHYS	-	Physical scrubbing
POM	-	Palm oil mill
POME	-	Palm oil mill effluent

PoPA	-	Power Pinch Analysis
PSA	-	Pressure swing adsorption
PV	-	Photovoltaic
QCP	-	Quadratic programming
RCN	-	Resource conservation network
SAHPPA	-	Stand-Alone Hybrid System Power Pinch Analysis
SHARPS	-	Systematic Hierarchical Approach for Resilient Process Screening
UAF	-	Up-flow anaerobic filtration
UASB	-	Up-flow anaerobic sludge blanket
US EPA	-	United States Environmental Protection Agency
USD	-	United States Dollar
WATS	-	Water scrubbing

LIST OF SYMBOLS

Σ - Summation

$\forall$ - All belong to

b - Type of anaerobic digestion technology

$BHP_{i,b,k,m,t,j}$ - Brake horsepower of compressor for production pathways *b*, *k*, and *t* with compression pressure *m* from supply location *i* to demand location *j*

$BHP_{i,t}^{\mathrm{C1}}$ - Brake horsepower of compressor for biogas allocation from palm oil mill *i* with production pathway *t*

$BHP_{t,p}^{\mathrm{C2}}$ - Brake horsepower of compressor for biomethane at centralised location *p* with production pathway *t*

$BHP_{i,t}^{\mathrm{C3}}$ - Brake horsepower of compressor for biomethane at palm oil mill *i* with production pathway *t*

BHP_{t}^{CNG} - Brake horsepower of compressor *t* for CNG supply chain

c - Gas mixture constituent

C^{AD} - Annual depreciation of purchased cost of anaerobic digester (USD/y)

C^{C} - Annual depreciation of purchased cost of compressor (USD/y)

C^{GC} - Annual depreciation of purchased cost of gas cylinder (USD/y)

C^{Trans} - Transportation cost (USD/y)

C^{U} - CAPEX of biogas upgrading (USD/y)

C^{B1} - Annual depreciation of purchased cost of gas cylinder for the distribution of biogas from POM to centralised location (USD/y)

C^{B2} - Annual depreciation of purchased cost of gas cylinder for the distribution of biomethane from centralised location to industrial demand (USD/y)

C^{B3} - Annual depreciation of purchased cost of gas cylinder for the distribution of biomethane from POM to industrial demand (USD/y)

C^{C1} - Annual depreciation of purchased cost of compressor for the distribution of biogas from POM to centralised location (USD/y)

C^{C2} - Annual depreciation of purchased cost of compressor for the distribution of biomethane from centralised location to industrial demand (USD/y)

C^{C3} - Annual depreciation of purchased cost of compressor for the distribution of biomethane from POM to industrial demand (USD/y)

C^{cU} - Upgrading cost of centralised production (USD/y)

C^{dU} - Upgrading cost of decentralised production (USD/y)

C^{TransPC} - Transportation cost from palm oil mills to centralised locations (USD/y)

C^{TransPCI} - Transportation cost from palm oil mills to centralised locations and then to industrial demands (USD/y)

C^{TransPI} - Transportation cost from palm oil mills to industrial demands (USD/y)

C^{Coal} - Cost of coal energy supply (USD/y)

$C^{\mathrm{C,CNG}}$ - Annual depreciation of purchased cost of compressor for CNG supply chain (USD/y)

$C^{\mathrm{GC,CNG}}$ - Annual depreciation of purchased cost of gas cylinder (USD/y)

C^{GR} - Cost of grid extension from existing grid networks to demand location

C^{LNG} - Cost of LNG import (USD/y)

C^{NG} - Purchasing cost of natural gas (USD/y)

$C^{\mathrm{Trans,CNG}}$ - Transportation cost for CNG supply chain (USD/y)

$\mathrm{D}_{i,j}$ - Transportation distance from supply location *i* to demand location *j* (km)

$\mathrm{D}_{p,j}^{\mathrm{CI}}$ - Distribution distance from centralised location *p* to demand location *j* (km)

$\mathrm{D}_{i,p}^{\mathrm{PC}}$ - Distribution distance from palm oil mill *i* to centralised location *p* (km)

$\mathrm{D}_{i,j}^{\mathrm{PI}}$ - Distribution distance from palm oil mill *i* to demand location *j* (km)

$\mathrm{D}_{j}^{\mathrm{Coal}}$ - Transportation distances from energy suppliers to demand location *j* for coal (km)

$\mathrm{D}_{j}^{\mathrm{CNG}}$ - Transportation distance from nearest natural gas grid to demand location *j* (km)

$\mathrm{D}_{j}^{\mathrm{GR}}$ - Straight line grid extension distance from existing natural gas grid to demand location *j* (km)

$\mathrm{D}_j^{\mathrm{LNG}}$ - Transportation distances from energy suppliers to demand location *j* for LNG import (km)

E^{D} - Industrial energy demand

$E_{i,b,k,m,t,j}^{\mathrm{eff}}$ - Effective energy supply of BioCNG of production pathways *k, m,* and *t* with compression pressure *m* from supply location *i* to demand location *j*

$E_{i,b,k,m,t,j}^{\mathrm{in}}$ - Energy content of production pathway *k* with compression pressure *m* from supply location *i* to demand location *j* (MJ/h)

$\mathrm{E}^{\mathrm{Methane}}$ - Energy content of pure methane (MJ/m^3)

$E_{i,b,k,m,t,j}^{\mathrm{Truck}}$ - Energy delivered by one truck of BioCNG of production pathways *k, m,* and *t* with compression pressure *m* from supply location *i* to demand location *j* (MJ/truck)

$E_{i,p}^{\mathrm{C1}}$ - Energy content of biogas from palm oil mill *i* to centralised location *p* (MJ/h)

$E_{p,j}^{\mathrm{C2}}$ - Energy content of biomethane at centralised location *p* to industrial demand *j* (MJ/h)

$E_{i,j}^{\mathrm{C3}}$ - Energy content of biomethane at palm oil mill *i* to industrial demand *j* (MJ/h)

$E_{i,p}^{\mathrm{C1Truck}}$ - Energy delivered by one truck of biogas from palm oil mill *i* to centralised location *p* (MJ/truck)

$E_{p,j}^{\mathrm{C2Truck}}$ - Energy delivered by one truck of biomethane from centralised location *p* to industrial demand *j* (MJ/truck)

$E_{i,j}^{\mathrm{C3Truck}}$ - Energy delivered by one truck of biomethane from palm oil mill *i* to industrial demand *j* (MJ/truck)

E^{eff} - Total effective energy supply of BioCNG from both centralised and decentralised production

E_j^{coal} - Energy allocation of coal to demand location *j* (GJ/y)

$E_{t,j}^{\mathrm{CNG}}$ - Energy supplied of CNG supply chain to demand location *j* with compressor *t* (MJ/h)

$\mathrm{E}_j^{\mathrm{D}}$ - Energy demand at demand location *j*

E_j^{GR} - Energy supplied of NG from grid extension to demand location *j* (MJ/h)

E_j^{LNG} - Energy allocation of LNG import for demand location *j* (GJ/y)

$E_{t,j}^{\mathrm{Truck,CNG}}$ - Energy delivered by one truck of CNG to demand location *j* with compressor *t* (MJ/truck)

$\mathrm{ED}^{\mathrm{Coal}}$ - Energy density of anthracite coal

$\mathrm{ED}^{\mathrm{LNG}}$ - Energy density of LNG

$\mathrm{ED}^{\mathrm{NG}}$ - Energy density of NG

$\mathrm{EF}_{k}^{\mathrm{BioCNG}}$ - GHG life-cycle assessment (LCA) emission factor of BioCNG supply chains with biogas upgrading technology k

$\mathrm{EF}^{\mathrm{CNG}}$ - GHG LCA emission factor of CNG supply chain

$\mathrm{EF}^{\mathrm{coal}}$ - GHG LCA emission factor of coal

$\mathrm{EF}^{\mathrm{GR}}$ - GHG LCA emission factor of NG

$\mathrm{EF}^{\mathrm{LNG}}$ - GHG LCA emission factor of LNG

$\mathrm{EF}^{\mathrm{Pipeline}}$ - GHG emission factor from pipeline transport (kg CO_2-eq/m^3•km)

$\mathrm{EF}^{\mathrm{Truck}}$ - GHG emission factor from truck transport (kg CO_2-eq/m^3•km)

$\mathrm{E}^{\mathrm{CP,biomethane}}$ - Energy content per unit volume of biomethane at cylinder pressure (MWh/m^3)

$\mathrm{E}^{\mathrm{CP,cylinder}}$ - Energy content at cylinder pressure per unit of cylinder (MWh/unit)

$\mathrm{E}^{\mathrm{eff,cylinder}}$ - Effective energy content of one BioCNG cylinder (MWh/unit)

$\mathrm{E}^{\mathrm{SP,biomethane}}$ - Energy content per unit volume of biomethane at suction pressure (MWh/m^3)

$\mathrm{GHG}^{\mathrm{C}}$ - Baseline emission level (Million kg CO_2-eq/y)

$GHG^{\mathrm{Processing}}$ - Emission generated from production processes of energy carriers for all energy pathways considered (Million kg CO_2-eq/y)

GHG^{T} - Target emission level (Million kg CO_2-eq/y)

GHG^{Trans} - GHG emission generated from distribution of energy carriers from processing plants to demand locations for all energy pathways considered

i - POME supply location

j - Location of selected industrial energy demand

k - Type of biogas upgrading technology

L - Useful life of equipment (y)

m - Biogas compression pressure of BioCNG cylinder

MinC - Minimum number of centralised BioCNG location

MinSC - Minimum total centralised biogas availability (m^3/h)

N^{GC} - Number of gas cylinder required per trip

$\mathrm{N}_{t}^{\mathrm{Stage}}$ - Numbers of stage compression t

$N_{i,b,k,m,t,j}^{\mathrm{Trip}}$ - Number of round trip required to transport BioCNG of production pathways *k*, *m*, and *t* with compression pressure *m* from supply location *i* to meet energy demand *j* (trip/h)

$\mathrm{n}^{\mathrm{real}}$ - Number of moles of the gas

$N_{p,j}^{\mathrm{CI}}$ - Number of round trip required to transport BioCNG from centralised location *p* to industrial demand *j*

$N_{i,p}^{\mathrm{PC}}$ - Number of round trip required to transport biogas from palm oil mill *i* to centralised location *p*

$N_{i,j}^{\mathrm{PI}}$ - Number of round trip required to transport BioCNG from palm oil mill *i* to industrial demand *j*

$N_{t,j}^{\mathrm{Trip,CNG}}$ - Number of round trip required to transport CNG to industrial demand *j* with compressor *t*

O^{AD} - Operating costs of anaerobic digester (USD/y)

O^{C} - OPEX of compressor (USD/y)

O^{e} - Electric utility cost of compression (USD/y)

O^{GC} - Operating costs of maintenance and repairing of gas cylinder (USD/y)

O^{U} - OPEX of biogas upgrading (USD/y)

O^{B} - OPEX of gas cylinder (USD/y)

O^{C} - OPEX of compressor (USD/y)

O^{cU} - OPEX of biogas upgrading for centralised production (USD/y)

O^{dU} - OPEX of biogas upgrading for decentralised production (USD/y)

$O^{\mathrm{C,CNG}}$ - OPEX of compressor for CNG supply chain (USD/y)

$O^{\mathrm{e,CNG}}$ - Electric utility cost of compression for CNG supply chain (USD/y)

$O^{\mathrm{GC,CNG}}$ - OPEX of gas cylinder for CNG supply chain (USD/y)

p - Centralised location of BioCNG production plant

$\mathrm{P}_{c}^{\mathrm{Critical}}$ - Critical pressure of gas mixture constituent *c* (kPa)

$\mathrm{P}_{k,m}^{\mathrm{D}}$ - Discard pressure after compression for production pathway *k* with compression pressure *m* (bar)

P^{in} - Suction pressure (bar)

$\mathrm{P}^{\mathrm{PCritical}}$ - Pseudocritical pressure

$\mathrm{P}^{\mathrm{PReduced}}$ - Pseudoreduced pressure

P^{real} - Absolute pressure of a gas

PT - Target percentage of emission reduction

P^{CP} - Cylinder pressure (bar)

P^{SP} - Suction pressure (bar)

$R^{\mathrm{C}}_{k,m}$ - Compression ratio for production pathway *k* with compression pressure *m*

R^{real} - Gas constant

R^{C1} - Compression ratio of biogas from suction pressure to 53.8 bar

R^{C2} - Compression ratio of biomethane from 53.8 bar to 215 bar

R^{C3} - Compression ratio of biomethane from suction pressure to 215 bar

$R^{\mathrm{C,CNG}}$ - Compression ratio for CNG production pathway

S^{biogas}_{i} - Availability of biogas in supply location *i* (m^3/h)

S^{NG}_{j} - Availability of natural gas from grid networks for demand location *j*

t - Type of biogas compression technology

T - Operating days (d/y)

$T^{\mathrm{Critical}}_{c}$ - Critical temperature of gas mixture constituent *c* (K)

$T^{\mathrm{PCritical}}$ - Pseudocritical temperature

T^{PReduced} - Pseudoreduced temperature

T^{real} - Absolute temperature of the gas

$V^{\mathrm{AD}}_{i,b}$ - Volume of anaerobic digester at palm oil mill *i* with production pathway *b* (m^3)

$V^{\mathrm{D}}_{i,b,k,m,t,j}$ - Discard volume of production pathways *b*, *k*, and *t* with compression pressure *m* from supply location *i* to demand location *j* (m^3/h)

V^{GC} - Volume of gas cylinder (m^3)

$V^{\mathrm{in}}_{i,b,k,m,t,j}$ - Inlet volume of production pathways *b*, *k*, and *t* with compression pressure *m* from supply location *i* to demand location *j* (m^3/h)

V^{real} - Volume of the gas

V^{Truck} - Capacity for one truck (m^3)

$V^{\mathrm{ce}}_{i,b,k,t,p,j}$ - Biogas allocation at palm oil mill *i* to centralised location *p* and then to industrial demand *j* with production pathways *b, k,* and *t* (m^3/h)

$V_{i,b,k,t,j}^{\mathrm{de}}$	-	Biogas allocation for decentralised production at palm oil mill *i* to industrial demand *j* with production pathways *b*, *k*, and *t* (m^3/h)
$V_{t,j}^{\mathrm{CNG}}$	-	Volume supplied of CNG supply chain to demand location *j* with compressor *t* (m^3/h)
$V_{t,j}^{\mathrm{D,CNG}}$	-	Discard volume of CNG supplied to demand location *j* with compressor *t* after compression (m^3/h)
$\mathrm{X}_b^{\mathrm{AD}}$	-	Cost parameter for anaerobic digestion technology *b*
$\mathrm{X}^{\mathrm{Compressibility}}$	-	Compressibility factor of gaseous mixture
$\mathrm{X}_{k,m}^{\mathrm{Compressibility}}$	-	Compressibility factor of energy carrier corresponding to production pathway *k* under compression pressure *m*
X^{D}	-	Cost parameter of transportation (USD/km)
X^{e}	-	Electric tariff in Malaysia (USD/kWh)
X^{GC}	-	Cost parameter of gas cylinder (USD/unit)
$\mathrm{X}_b^{\mathrm{HRT}}$	-	Hydraulic retention time corresponding to anaerobic digestion technology *b* (days)
$\mathrm{X}_k^{\mathrm{Methane}}$	-	Methane content of production pathway *k*
$\mathrm{X}^{\mathrm{M\&S}}$	-	Marshall and Swift equipment cost index
$\mathrm{X}_c^{\mathrm{mol}}$	-	Mole fraction of gas constituent *c*
$\mathrm{X}_t^{\mathrm{Stage}}$	-	Coefficient corresponding to numbers of stage compression *t*
$\mathrm{X}_k^{\mathrm{U}}$	-	Cost parameter for biogas upgrading technology *k*
$\mathrm{X}^{\mathrm{ComBiogas}}$	-	Compressibility factor of biogas at 53.8 bar
$\mathrm{X}^{\mathrm{ComBiomethane}}$	-	Compressibility factor of biomethane at 215 bar
$\mathrm{X}^{\mathrm{Biogas}}$	-	Methane content of biogas
$\mathrm{X}^{\mathrm{Biomethane}}$	-	Methane content of biomethane
$\mathrm{X}^{\mathrm{coal}}$	-	Coal price (USD/GJ)
$\mathrm{X}^{\mathrm{ComCNG}}$	-	Compressibility factor of NG at 215 bar
X^{GR}	-	Cost parameter of grid extension (USD/km)
X^{ip}	-	LNG import price (USD/GJ)
$\mathrm{X}^{\mathrm{MethaneCNG}}$	-	Methane content of natural gas
X^{NG}	-	NG price (USD/GJ)
X^{rp}	-	LNG regasification cost (USD/GJ)
y_p	-	Binary variable for selection of centralised location *p*

y_j^{GR} - Binary variable of grid extension to demand location *j*

Z^{BVPO} - Total cost of BioCNG energy supply in BVPO model (USD/y)

Z^{BND} - Total cost of BioCNG production in BND model (USD/y)

Z^{EAEEA} - Total cost of energy supplies including BioCNG energy supplies, CNG supply chain, NG from grid extension, LNG import and coal (USD/y)

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

According to Ministry of Energy, Green Technology and Water (KeTTHA) (2017), Malaysia has guaranteed to reduce carbon emission intensity by a maximum of 45 % by the year 2020 with 2005 baseline. Energy consumption for industrial sector contributes to a significant amount for total energy usage in Malaysia. Industrial energy usage in Malaysia at year 2013 was estimated as 565.1 PJ, which was equivalent to 26.2 % of total national energy consumption (Energy Commission, 2015). Energy Commission (2015) also stated that energy supplies such as natural gas, coal and oil are still widely been used for commercial energy demand and electricity generation in Malaysia. It is inevitable that country's future growth will increase national energy demand. If usage of fossil fuels in energy mix remains as the main energy source, CO_2 emission will continue to increase. Emission level exceeded to 157.5 Mt by 2003 and the year afterwards. According to Energy Information Administration (EIA), energy demand increased at a rate of 5 % to 7.9 % annually for the next 20 years from 2004 onwards (EIA, 2006). If future energy demand continues to increase at this rate, energy security is becoming a serious issue because fossil fuel is a non-renewable energy and will eventually deplete. In this study, biocompressed natural gas (BioCNG) energy supply is proposed to mitigate the greenhouse gas (GHG) emission and meet the industrial energy demand simultaneously.

Energy is one of the most important driving force of economy and modernization of a country. In fact, global energy demand increases significantly that it is increased from 14.5 × 10^{10} MW in 2007 to 21.8 × 10^{10} MW in 2035 (Hasanuzzaman et al., 2012). Solar panels, wind turbines, biomass energy and micro hydro power plants are among promising renewable energy sources in Malaysia. Biogas has shown promising development since 2013 due to the Feed-in Tariff mechanism under the enforcement of the Renewable Energy Act 2011 (Hashim and Ho, 2011). Biogas could be generated from palm oil mill effluent (POME), landfill gas, and organic waste through anaerobic digestion.

1.1.1 From Palm Oil Mill Effluent (POME) to Biocompressed Natural Gas (BioCNG)

Biogas is produced by anaerobic digestion of POME and it can be upgraded to higher energy density product that is biomethane. Biomethane is recognized to be a higher grade fuel than biogas because it is less corrosive and higher energy content than biogas. Biomethane can be further compressed and stored for future use. Such compressed biomethane is also known as BioCNG. Biomethane will eventually be transported to end users. BioCNG can be utilized as heat, combined heat and power (CHP) and transportation fuel (Mshandete and Parawira, 2009).

As the second world largest palm oil mill exporter in the world, huge amount of POME generated in Malaysia. In this study, POME is proposed as a feedstock for BioCNG production due to the abundant supply in Malaysia and its high organic contents. Moreover, POME contains biodegradable constituents with a biological oxygen demand (BOD) to chemical oxygen demand (COD) ratio of 0.5 and this implies that POME can be treated easily using biological means (Metcalf, 2003). POME produced huge amount of biogas from its anaerobic process and it can reach to 15 billion m^3 annually (Zafar, 2015).

Potential power generation from POME generated is 4,179,168 MWh in year 2014 as reported by Environmental Technology Research Centre of Standard and

Industrial Research Institute of Malaysia (ETRC SIRIM) (2014). The excess electricity from undigested POME is 4,127,551.3 MWh. Currently, application of biogas is mainly for palm oil mills on-site energy demand or natural gas grid injection through feed-in-tariff (FiT) mechanism (ETRC SIRIM, 2014). The potential for transporting upgraded biogas for industrial usage is yet to be explored. This is due to the excess amount of biogas generated onsite as indicated in Table 1.1.

Table 1.1 Sample of excess amount of biogas generation (ETRC SIRIM, 2014)

Palm Oil Mill	POME Capacity (m^3/y)	Potential Electricity Generation (MW)	Electricity Injected to Grid (MW)	Excess energy (MW)	Excess of biogas (m^3/y)
Johor Labis	216,000	1.44	1.25	0.19	285,326
Kilang Kelapa Sawit Serting	194,000	1.30	1.10	0.20	300,343

Transportation by trail is commonly known as a virtual pipeline and is the most suitable alternative for remote energy distribution. A commercialised virtual pipeline usually consists of three interdependent components, namely the mother station (compression), the transportation and the consumption station/gas district station (Udaeta et al., 2012). Virtual pipelines are substitute to physical pipelines that distribute natural gas via land or sea transport for industrial usage. The virtual natural gas pipeline replicates the continuous flow of a static physical natural gas pipeline, delivering energy where physical pipelines is immature or non-existent. Gas is processed and compressed at its source location, and made readily available for fuel replacement in industry. Biogas as fuel for transportation, has been pioneered and tested by Sime Darby by pressurising up to 250 bar (Nasrin et al., 2017). The compressed or liquefied gas can be transported to another location for use, in various applications ranging from fuel displacement for industrial usage, power generation and natural gas vehicle (NGV) fuelling. In this study, virtual pipeline of BioCNG is considered.

1.1.2 BioCNG as a Promising Energy Supply

One believes in bioenergy as significant in meeting the sustainable development goals of renewable energy and climate change; the other criticizing bioenergy as an inefficient renewable energy in contrast to solar and wind energy (Pfau et al., 2017). It is estimated that by 2030 ‘modern bioenergy’ (produced by using biomass technologies like biorefineries, anaerobic digestion of residues, bioreactors for torrefaction, carbonization, or gasification, and other technologies) would reach the potential of being the most highly growing renewable energy source (IRENA, 2016).

Chandra et al. (2011) compared the performance of a constant speed internal combustion engine using CNG and conventional BioCNG. The findings of their research show that engine performances for regular CNG and conventional BioCNG were similar in terms of brake power output, specific gas consumption, and thermal efficiency. Another study carried out by Subramanian et al. (2013) also showed no significant difference in vehicle fuel economy and emissions of regular CNG and conventional BioCNG.

Emissions from engine with bus operated on BioCNG were compared to that of diesel fuels. The results showed that there was substantial decrease in emissions from BioCNG buses (Ryan and Caulfield, 2010). Under suitable modifications vehicle can be operated on BioCNG and few countries in world having BioCNG fuelling stations. As far as global warming potential is considered BioCNG is way better than fossil fuels like CNG and gasoline. A case study which was carried out in Ireland showed that oil replacement with biomethane would directly save € 500 million out of € 5.9 billion (Thamsiriroj et al., 2011). A 5.9 kW stationary diesel engine was converted to spark ignition engine to operate on CNG, BioCNG and biogas generated from Jatropha and Pongamia oil seed cakes (Chandra et al., 2011). The BioCNG showed similar engine performance as compared to CNG in terms of brake horse power and specific gas consumption.

By compressing the biogas reduces storage requirements, concentrates energy content and increases pressure level required to overcome resistance to gas flow (Singh et al., 2016). A case study was carried out on feasibility of filling biogas into cylinders in Punjab, India. The biogas generated from corporation area was 28 m^3 which was then purified, compressed and filled into cylinders. The gas was sufficient to provide fuel for 85,000 people (Verma and Samanta, 2016). A project was undertaken to compress and store biogas generated from kitchen waste. A foot lever compressor was designed and biogas was compressed to 4 bars in 0.5 m^3 tank (Ray et al., 2016).

Johnathon and Ajay (2018) compared the techno-economic feasibility of four different pathways of upgrading biogas to value-added products. These four pathways are the production of 1) purified biogas for grid injection; 2) BioCNG; 3) methanol via thermochemical conversion; and 4) methanol via biological conversion using methane-oxidizing bacteria. They concluded that BioCNG had the highest net present value (NPV), followed by purified biogas for grid injection, biological methanol production, and thermochemical methanol production. Moreover, Nasrin et al. (2020) demonstrated that the integrating biogas and BioCNG plant in palm oil mill is a viable business model, technically and economically, in providing commercial and environmental benefits to palm oil industry and industrial users. Hence, BioCNG energy supply is selected to be investigated in this study.

1.2 Problem Statement

POME is the most potential biogas feedstock which is accounted for 99.8 % of total potential energy generation when compared to biogas feedstocks of cattle livestock and landfill in Malaysia (Gopinathan et al., 2018). This quantity represents a sizeable opportunity to produce new wealth creation through biogas for industrial usage. Following are the gaps identified in the current research on biogas for industrial usage.

1. Biogas as fuel for transportation had been pioneering tested by Sime Darby which the biogas was pressurized up to 250 bar (Nasrin et al., 2017), however,

this high pressure may not be necessary for industrial demand. High compression pressure will lead to high compression costs while reducing transportation costs due to higher energy density in BioCNG cylinder. None of the research investigated the trade-off between compression pressure of BioCNG cylinder and the cost of transportation. Hence, determination of optimum compression pressure of BioCNG cylinder is essential to make biogas for industrial usage becomes economically viable.

2. Palm oil mills are mostly located in rural areas where energy demands are low, any form of energy based on POME whether it is electricity or BioCNG has to be transported to a local town which is often over 10 km away from the palm oil mills (Mohtar et al., 2017). None of the research considered detail transportation networks involved on distribution of BioCNG cylinder. Hence, supply cost curve for various transportation networks such as decentralised and centralised system should be considered for accurate cost estimations.

3. BioCNG cylinder can be considered as energy storage. Nevertheless, none of the studies examined the optimal scheduling of BioCNG to fulfil dynamic industrial demand. Moreover, energy supply of BioCNG cylinder can only take certain values with gap of energy content of one cylinder. The energy supply of BioCNG cylinder is different than pipeline transport of energy which can take any values given that the values are positive. Hence, this atypical concept of energy storage with BioCNG cylinder should be investigated.

1.3 Objectives of the Study

The main aim of this research is to develop a comprehensive and systematic framework for BioCNG supply chain with POME feedstock to end user of industrial demand. In order to achieve the ultimate goal of this research, four objectives are listed as follow:

i. To develop an operational model of BioCNG supply chain in order to determine optimum compression pressure of BioCNG cylinder and its feasibility for industrial purposes.

ii. To develop a spatial explicit optimization model of BioCNG supply chain in order to optimize the network design of BioCNG distribution networks with the consideration of centralisation and decentralisation production.

iii. To determine optimal energy allocation of BioCNG among other energy alternatives for industrial demand with environmental and cost consideration.

iv. To investigate optimal scheduling of BioCNG supply chain for dynamic industrial demand with the consideration of BioCNG cylinder as energy storage.

1.4 Scope of the Study

A number of scopes related to studied research objectives have been identified as follow:

1. Developing an optimization model related to operational aspects in order to determine optimum compression pressure of BioCNG cylinder and its feasibility for industrial purposes. This optimization model should be able to identify:

    i. Correlation of optimum compression pressure of BioCNG cylinder with transportation distance between POM and industrial demand.
    ii. Cost breakdown of BioCNG supply chain with respect to increasing compression pressure.

    iii. Standardised compression pressure of BioCNG supply chain and its feasibility. Standardized compression pressure is defined as a single selected compression pressure used for all BioCNG cylinder distributions instead of assigning particular compression pressure for each distributions.

2. Developing a spatial explicit optimization model of BioCNG supply chain in order to optimize the network design of BioCNG distribution networks with the consideration of centralisation and decentralisation production. This optimization model should be able to identify:

    i. Cost comparison of centralised and decentralised production of BioCNG supply chains.
    ii. Optimum location and capacity of centralised processing plant of BioCNG supply chain.

3. Developing an optimization model to determine optimal energy allocation of BioCNG among other energy alternatives for industrial demand with environmental and cost consideration. This optimization model should be able to identify:

    i. Supply cost factors of each energy pathways from source locations to demand locations. Energy pathways considered are BioCNG supply chains with and without biogas upgrading, Compressed Natural Gas (CNG) production, Natural Gas (NG) from grid extension, Liquefied Natural Gas (LNG) import and coal.
    ii. Optimal energy mix of energy pathways to meet GHG emission target with minimum total cost of energy supply.

4. Developing priority ranking of energy substitutions and integrated spatial pinch analysis to investigate progressive steps of energy substitutions to achieve optimal energy mix with environmental and cost considerations. These ranking and analysis should be able to identify:

   i. Best energy substitution based on original energy mix of selected industrial demand.
   ii. Graphical representations of progressive steps of energy substitutions to achieve optimal energy mix.

5. Developing a spatial analysis to compare total cost of energy pathways in spatial attributes with the consideration of undeveloped area with non-existent road networks. This analysis should be able to identify:

   i. Geographical influences of source and demand locations towards the cost differences among energy pathways.

6. Developing a pinch analysis to investigate optimal scheduling of BioCNG supply chain for dynamic industrial demand with the consideration of BioCNG cylinder as energy storage. This analysis should be able to identify:

   i. BioCNG purchasing amount, inventory storage size, initial inventory, and outsource energy amount.

1.5 Significance of Study

The main contribution of this research is to produce a structural and comprehensive framework based on optimization modelling approach and integrated pinch analysis approach to evaluate the economic and environmental impacts for the development of a sustainable energy hub involving BioCNG energy supply. The specific research contributions are described as follows:

1. An optimized BioCNG supply chain is generated with optimization in terms of operational and spatial aspects. These include operational production of BioCNG and network design of its distribution networks to optimize BioCNG supply chain. The developed methodologies based on real time situation can

be utilized by decision makers to invest in BioCNG supply chain with minimum cost.

2. This research also evaluates the potential of BioCNG supply chain for improving current energy mix. Optimal energy allocation of BioCNG supply chain among other energy alternatives considered that are LNG import, CNG, NG from grid extension, and coal is successfully determined. The findings can be used as a guideline for decision makers to develop a more cost effective and environmental friendly energy mix.

3. Ranking of energy substitution operations is determined to show priority energy substitution steps to be taken for decision makers. The priority ranking is especially beneficial when financial resource is limited to implement optimum energy mix.

4. Optimal scheduling of BioCNG supply chain with the consideration of dynamic industrial energy demand is determined. Optimal scheduling of BioCNG supply chain provides decision makers with the theoretical values of BioCNG purchasing amount, inventory storage size, initial inventory, and outsource energy amount.

5. All of the optimization models and analysis are generalized to provide flexibility for application in other locations and introducing new technologies or energy alternatives. It opens opportunities for the models and analysis to be further applied to the whole Malaysia, or even other countries. The generalized methodologies also provide future-proof assistance to decision makers for comparing BioCNG supply chain with any future energy supplies developed.

1.6 Thesis Outline

Overall, this thesis comprises of eight chapters, a graphical presentation of the entire studies performed in this thesis work is shown as Figure 1.1.

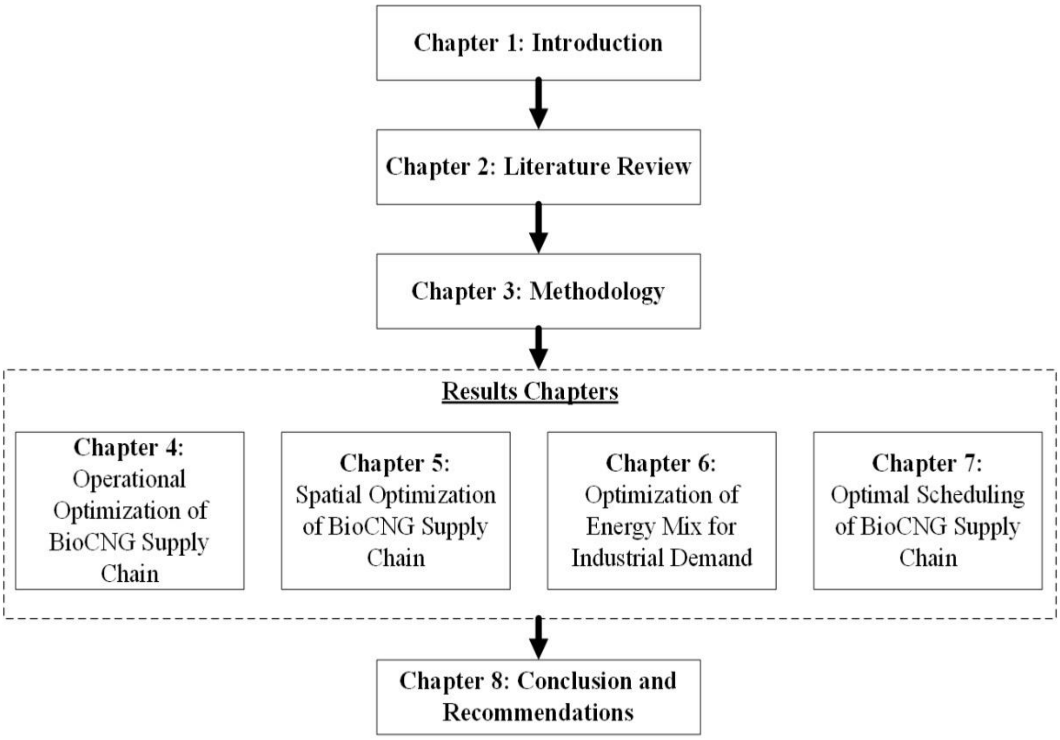

Figure 1.1 Thesis outline

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Lee, M. K.**, Hashim, H., Lim, J. S., & Taib, M. R. (2019). Spatial planning and optimisation for virtual distribution of BioCNG derived from palm oil mill effluent to meet industrial energy demand. *Renewable Energy*, *141*, 526–540. https://doi.org/ 10.1016/j.renene.2019.03.097. **(Q1, IF:6.274)**
2. **Lee, M. K.**, Hashim, H., Ho, W. S., Zarina, A. M., Yunus, N. A., & Xu, H. (2020). Integrated spatial and pinch analysis of optimal industrial energy supply mix with consideration of BioCNG derived from palm oil mill effluent. *Energy*, *209*, 118349. https://doi.org/10.1016/j.energy.2020.118349. **(Q1, IF:6.082)**

Indexed Journal

1. **Lee, M. K.**, Hashim, H., Ho, C., Ho, W. S., & Lim, J. S. (2017). Economic and Environmental Assessment for Integrated Biogas Upgrading with CO_2 Utilization in Palm Oil Mill, *Chemical Engineering Transactions*, *56*, 715–720. https://doi.org/10.3303/CET1756120. **(Indexed by SCOPUS)**

2. **Lee, M. K.**, Hashim, H., Ying, H., Ho, W. S., Yunus, N. A., & Lim, J. S. (2017). Biogas Generated from Palm Oil Mill Effluent for Rural Electrification and Environmental Sustainability, *Chemical Engineering Transactions*, *61*, 537–1542. https://doi:10.3303/CET1761254. **(Indexed by SCOPUS)**