OPTIMAL PLANNING OF HYBRID POWER GENERATION SYSTEM TOWARDS LOW CARBON DEVELOPMENT

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OPTIMAL PLANNING OF HYBRID POWER GENERATION SYSTEM
TOWARDS LOW CARBON DEVELOPMENT

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I declare that this thesis entitled "*Optimal Planning of Hybrid Power Generation System Towards Low Carbon Development*" is the result of my own research except as cited in references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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This thesis is especially dedicated to my husband, Muhammad bin Mat Junoh, my beloved children, Nur Nabilah and Muhammad Farhanuddin, my beloved parents, Ab Muis bin Mohd and Bidah bt Karim, my mother in law, Kamariah bt Hamat and not forgotten my late father in law,Mat Junoh bin Yaakob. You are all the sources of my strength. May Allah bless us all forever.

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ABSTRACT

In Malaysia, the energy sector is identified as one of the major carbon dioxide (CO_2) emitters. Electricity in Malaysia is primarily generated from coal, natural gas, diesel, oil and hydro. The government of Malaysia encourages power producers to shift towards the use of renewable energy (RE) and reduce their reliance on fossil fuels. There is a clear need for a systematic method to sustainably plan the fleet-wide electricity generation and capacity expansion towards fulfilling the forecasted electricity demand and simultaneously meet the emission reduction target. A comprehensive superstructure consisting of all existing (i.e. Pulverized Coal (PC), Natural Gas Open Cycle (NGOC)) and new power generation technologies (i.e., Natural Gas Combined Cycle (NGCC), nuclear, solar, biomass and Municipal Solid Waste (MSW)) was constructed at the early stage of model development in this study. Towards this end, three different models have been developed and implemented in the General Algebraic Modeling System (GAMS) as follows: 1) Single period model for electricity generation mix that is designed to satisfy the electricity demand until the year 2020 for Peninsular Malaysia, 2) Multi period model for selection of power generation technology that is designed to satisfy the forecasted electricity demand from year 2012 to 2025 in Iskandar Malaysia (IM) and 3) Multi-period optimization model that is developed to determine the optimal location of new RE generation stations to reduce transmission losses and transportation cost in IM. Options are made available by models 1 and 2 to switch the coal plants to natural gas power plants and to increase the use of renewable energy in order to meet CO_2 target and to minimize cost. Model 3 is capable of predicting the cost-optimal generation capacity, type of biomass-energy conversion technology and location for the construction and operation of new biomass power plants. The models can provide vital tools to assist the government in policy making.

ABSTRAK

Di Malaysia, sektor tenaga dikenalpasti sebagai penyumbang utama pembebasan karbon dioksida (CO_2). Penjanaan elektrik utama di Malaysia adalah daripada arang batu, gas asli, diesel, minyak dan hidro. Kerajaan Malaysia menggalakkan penjana tenaga untuk beralih ke arah penggunaan tenaga diperbaharui dan mengurangkan pergantungan kepada bahan api fosil. Sangat jelas bahawa kaedah yang sistematik untuk merancang secara lestari penjanaan *fleet-wide* dan penambahan kapasiti elektrik ke arah memenuhi ramalan kehendak elektrik dan dalam masa yang sama mencapai matlamat pengurangan pembebasan karbon dioksida. Satu struktur super yang komprehensif terdiri daripada semua jenis penjana elektrik sedia ada, (arang batu terhancur (PC), kitaran terbuka gas asli (NGOC)) dan teknologi penjanaan yang baru (iaitu gas asli kitar padu (NGCC), nuklear, solar, bio-jisim dan sisa buangan pepejal (MSW)) telah dibina pada peringkat awal pembinaan model di dalam kajian ini. Pada akhirnya, tiga model yang berbeza telah dibina dan digunakan di dalam General Algebraic Modeling System (GAMS), seperti berikut: 1) Model tempoh tunggal untuk campuran penjanaan elektrik yang direka untuk memenuhi kehendak keperluan elektrik pada tahun 2020 untuk Semenanjung Malaysia, 2) Model tempoh berganda untuk pemilihan teknologi penjanaan yang direka untuk memenuhi ramalan keperluan elektrik dari tahun 2013 hingga 2025 di Iskandar Malaysia (IM) dan 3) Model tempoh berganda yang dibina untuk menentukan lokasi yang optimum untuk pembinaan loji penjanaan tenaga diperbaharui untuk mengurangkan kehilangan penghantaran elektrik dan kos pengangkutan di IM. Pilihan telah diwujudkan dalam model 1 dan 2 untuk menukar loji janakuasa arang batu kepada loji janakuasa gas asli dan meningkatkan penggunaan tenaga diperbaharui untuk mencapai matlamat pengurangan CO_2 dan meminimumkan kos. Model 3 berupaya untuk meramalkan kos optimum bagi kapasiti penjanaan, jenis teknologi biojisim-tenaga dan lokasi untuk pembinaan dan pengoperasian loji janakuasa biojisim yang baru. Model-model ini menyediakan peranti penting bagi membantu kerajaan dalam pembangunan polisi.

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LIST OF ABBREVIATIONS

°C	-	Degree Celcius
AC	-	alternating current
BioGen	-	Biomass Generation and Demonstration
CDM	-	clean development mechanism
CETREE	-	Centre for Education and Training in Renewable Energy and Energy Efficiency
CH_4	-	methane
CO	-	carbon monoxide
CO_2	-	Carbon dioxide
COE	-	Cost of Electricity
DANIDA	-	Danish International Development Agency
DC	-	direct current
DEG	-	Distributed energy generation
EFB	-	Empty Fruit Bunches
EFOM	-	energy flow optimisation model
EPM	-	Energy planning model
FiT	-	Feed-in Tariff
GA	-	genetic algorithm
GAMS	-	General Algebraic Modeling System
GDP	-	Gross Domestic Product
GHG	-	greenhouse gases
GOM	-	government of Malaysia
GWh	-	Gigawatthour

HCl	-	hydrochloric acid
HFCs	-	hydrofluorocarbons
HV	-	heating value
IEA	-	International Energy Agency
IGCC	-	Integrated gasification combined cycle
IM	-	Iskandar Malaysia
IPP	-	Independent Power Producer
KeTTHA	-	Ministry of Energy, Green Technology and Water
kJ/kg	-	Kilojoule/kilogram
kWh	-	Kilowatthour
LNG	-	liquefied natural gas
LP	-	Linear Programming
LULUCF	-	land use, land-use change and forestry
MBIPV	-	Malaysia Building Integrated Photovoltaic
MILP	-	Mixed Integer Linear Programming
MINLP	-	Mixed Integer Non Linear Programming
MIP	-	integer programming
MMt	-	million metric tonnes
MOLP	-	Multi Objectives Linear Programming
MSW	-	Municipal Solid Waste
mtoe	-	Metric tonnes oil equivalent
MW	-	Megawatts
N_2O	-	nitrous oxide
NG	-	natural gas
NGCC	-	Natural gas combined cycle
NGOC	-	Natural Gas Open Cycle
NLP	-	Non Linear Programming
NOx	-	nitrogen oxide
O&M	-	operation and maintenance
PC	-	Pulverised Coal
PETRONAS	-	Petroleam Nasional Berhad
PFCs	-	perfluorocarbons
PJ	-	Petajoule

PKS	-	Palm kernel shell
POME	-	palm oil mill effluent
PV	-	Photovoltaic
RE	-	renewable energy
RES	-	renewable energy sources
SCORE	-	Sarawak Corridor of Renewable Energy
SF_6	-	sulphur hexafluoride
SOx	-	sulphur oxide
SREP	-	Small Renewable Energy Power
Tcf	-	Trillion cubic feet
TNB	-	Tenaga National Berhad
UNDP	-	United Nations Development Programme
UNFCC	-	United Nations Framework Convention on Climate Change
Wp	-	Watt power

LIST OF SYMBOLS

$A_{biom,t}^b$	-	Biomass availability in year 't' (GJ)
A_c^C	-	annual capacity factor for coal power plant
A_f^F	-	annual capacity factor for new fossil fuel power plant
A_g^G	-	annual capacity factor for NG power plant
A_r^R	-	annual capacity factor for renewable energy power plant
ACF^b	-	Annual capacity factor for biomass power plant
b	-	biomass
B_i	-	Existing biomass power plants
B_i^{new}	-	New biomass power plants
B_{bt}	-	renewable resources consumption amount during year 't'
BG	-	biogas availability
BGE	-	biogas lower heating value
C_i	-	Existing coal power plants
$Cap_{tech,lc,tc}^b$	-	Capital cost of biomass type 'b'plant size, built in year 'tc', and operates in year 't' (MW) using technology, "$tech$" at location "lc"
CD_t	-	Capacity demand during year 't'
$CO2^C$	-	CO_2emission of coal
$CO2^G$	-	CO_2 emission of natural gas
$CO2_f^F$	-	CO_2 emission of fuel for new fossil fuel power plant (coal and natural gas)
$CO2lim$	-	CO_2 emission limit

D_i	-	Existing diesel power plants
E_b^R	-	heating value of the resource
E_{ij}	-	Actual electricity generation from ith fossil fuel using jth fuel type for existing power plant (MWh)
E_j	-	Actual electricity generation from non fossil fuel (MWh)
E_j^{new}	-	Electricity generation for new power plant (MWh)
$e_{tech,lc,tc,t}^b$	-	Electricity generation (MW) from biomass type 'b' using technology type '$tech$', at location 'lc' to be build in year 'tc'
ED_{lt}	-	energy demand in period 'l' during year 't'
Ef	-	efficiency of solar PV modules
F	-	Fossil fueled power plants
$FOM_{tc,t}^b$	-	Fixed O&M cost for biomass power plant built in year 'tc', and operates in year 't'(RM/MW)
H_i	-	Existing hydroelectric power plants
H_i^{new}	-	New hydroelectric power plants
H_c^C	-	heat rate of the coal power plant
H_{fdt}^F	-	heat rate of the new fossil fuel power plant during year 't'
H_g^G	-	heat rate of the NG power plant
HR_{tech}^b	-	Heat rate for biomass type 'b'(MW) for technology, "$tech$" (GJ/MWh)
i	-	power stations
I^C	-	operating and maintenance (O&M) cost of the coal power plant
I^G	-	operating and maintenance (O&M) cost of the NG power plant
I_{fdt}^F	-	operating and maintenance (O&M) cost of the NG power plant
I_{rdt}^R	-	operating and maintenance (O&M) cost of the new renewable energy power plant
IG_i^{new}	-	New IGCC power plants
In	-	average solar intensity

j	-	fuels
L	-	Transmission loss
LA	-	land area availability
lb	-	Palm oil mill
lc	-	Locations
LFG	-	capacity of landfills
$LCD_{lc,subt}$	-	Distance from location of power plant to substation location (km)
$LBD_{lb,lc}$	-	Distance from palm oil mill to location of power plant (km)
$Loss$	-	Transmission and distribution loss
LP_{lc}	-	Land price for location 'lc' (RM per ft^2)
M	-	waste allocated for direct incineration
M_i^{new}	-	Operating & Maintenance (O&M) cost for new power stations (RM/MWh)
ME	-	lower heating value of the solid wastes
MG	-	waste allocated for landfill gas capturing
MGE	-	lower heating value of landfill gas
MSW	-	total MSW generated annually
N_{rdt}^F	-	construction lead time for fossil fuel power plant
N_{rdt}^R	-	construction lead time for RE power plant
new	-	New power plants
NF	-	Non-fossil fueled power plants
NG_i	-	Existing natural gas power plants
NG_i^{new}	-	New natural gas combined cycle power plants
N_i^{new}	-	New nuclear power plants
O_l	-	operation hour for on-off peak periods
O_i	-	Existing oil power plants
$optime$	-	Annual operating time (hours/year)
P^b	-	Price of biomass (RM per GJ)
PB_b	-	price of renewable resources
PC_t	-	price of coal in year 't'
PC_i^{new},	-	New pulverized coal power plants

PF_{ft}	-	price of fossil fuel in year 't'
PG_t	-	price of NG in year 't'
R_{ij}	-	Retrofit cost (RM/MW)
RM	-	reserve margin
S_c^C	-	capacity of the existing coal power plant
S_{fd}^F	-	capacity of the new fossil fuel power plant
S_g^G	-	capacity of the existing natural gas power plant
S_{rd}^R	-	capacity of the new renewable energy power plant
S_i^{new}	-	Capital cost for new power plant (RM/MW)
SG	-	sewage gas availability
SGE	-	sewage gas lower heating value
SO_i^{ne}	-	New solar power plants
$subt$	-	substations
t	-	Time horizon of planning
T_{fdt}^F	-	capital cost of the new fossil fuel power plant in year 't'
T_{rdt}^R	-	capital cost of the new renewable energy power plant in year 't'
tc	-	Time horizon of building
$tech$	-	energy conversion technologies
TR	-	Construction trend
V^C	-	variable O&M cost for coal power plant
V^G	-	variable O&M cost for NG power plant
V_{fdt}^F	-	variable O&M cost for new fossil fuel power plant
V_{rdt}^R	-	variable O&M cost for new renewable energy power plant
V_{ij}	-	Operating & maintenance (O&M) cost for existing power stations (RM/MWh)
$VOM_{tech,tc,t}^b$	-	Variable O&M cost for biomass power plant built in year 'tc', and operates in year 't'(RM/MWh)
W_{ctl}^C	-	power generated by the coal power plant in period 'l' during year 't'
W_{fdtl}^F	-	power generated by the new fossil fuel power plant in period 'l' during year 't'

W_{gtl}^{G}	-	power generated by the NG power plant in period '*l*' during year '*t*'
W_{rdtl}^{R}	-	power generated by the new renewable energy power plant in period '*l*' during year '*t*'
W_i^{new}	-	New wind power plants
$X_{tech,lc,tc}^{b}$	-	Amount of biomass power plant to be build in year '*tc*' (MW), b= type of biomass, using technology, "*tech*" at location "*lc*".
X_{ct}^{C}	-	binary variable of the existing coal power plant during year '*t*'(1 indicates plant in operation while 0 indicates plant shut down)
X_{gt}^{G}	-	binary variable of the existing NG power plant during year '*t*'(1 indicates plant in operation while 0 indicates plant shut down)
x_{ij}	-	Binary variable ; 1 if coal-fired boiler *i* is operational using fuel *j*; 0 otherwise
y_i	-	Binary variable ; 1 if power plant *i* is operational; 0 otherwise

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CHAPTER 1

INTRODUCTION

1.1   Current Scenario of Electricity Generation in Malaysia

In Malaysia, natural gas, coal, diesel, fuel oil (distillate), hydro and biomass are used to generate electricity. The share of natural gas, as energy input into power stations, has decreased from 62.30% in 2005 to 55.52% in 2010. The share of coal, however, has slightly increased from 28.10% in 2005 to 28.26% in 2010. As for the other forms of energy input, the share of hydro accounted for 7.78%, while the remainder was provided by diesel and fuel oil at 4.7% and 0.95% each, respectively. Installed capacity and generation mix by fuel type are indicated in the pie charts shown in Figure 1.1 and Figure 1.2 (Energy Commission, 2012).

The total electricity consumption for Malaysia recorded a growth from 81.243 billion kWh in 2006 to 127.069 billion kWh in 2011. The share in electricity demand was highest for the industrial sector at 48.5%, followed by the commercial sector at 31.3% and the residential sector at 20.1%. Nevertheless, under a four-fuel diversification strategy, the power sector has successfully decreased its dependency on oil (Ministry of Energy, Water and Communication, 2005). In 2006, biomass-based renewable energy (RE) plants were operating to create 441 MW (Energy Commission, 2008). In 2011, RE (biomass-based) generated 1538 GWh from 740 MW power plants (Energy Commission, 2012).
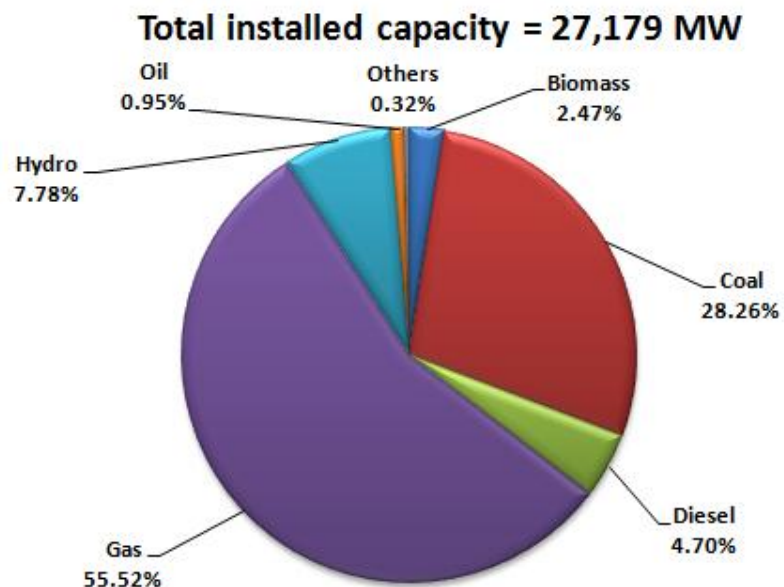
Figure 1.1 Malaysia's Current Installed Capacity by Fuel Type (Energy Commission, 2012).
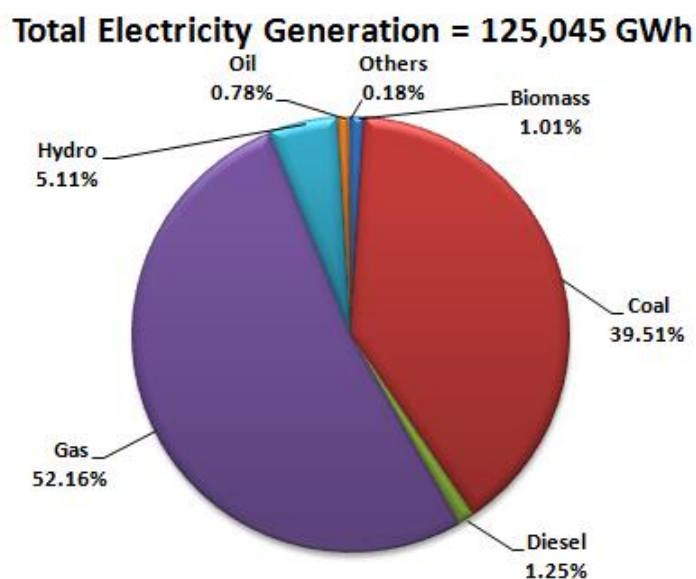
Figure 1.2 Malaysia's Electricity Generation by Fuel Type (Energy Commission, 2012).

The discovery of new gas fields contributed to the increase in reserves from 84.3 trillion cubic feet (tcf) in 2000 to 88.93 trillion cubic feet (tcf) in January 2008 and is expected to last for 33 years (Gas Malaysia Sdn. Bhd., 2009). The

government heavily subsidised natural gas (NG) to attract investors to its abundant resources. As a consequence, electricity generation from NG became the most attractive fuel option and contributed up to 52.16 % of electricity generation, followed by coal at 39.51%, hydro at 5.11%, diesel at 1.25 %, biomass at 1.01 %, fuel oil at 0.78 % and others at 0.18% – as shown in Figure 1.2 (Energy Commission, 2012). In early June 2008, the government announced the restructuring of fuel subsidies amidst the continuing global escalation of oil prices. Therefore, with the new electricity tariff rates, the average selling price decreased to 31.31 sen/kWh compared to the previous average selling price of 31.54 sen/kWh (Energy Commission, 2010).

Having learned a lesson from the world oil crises of 1973 and 1979, in the 8th Malaysia Plan (from 2001 to 2005) the government initiated the five-fuel diversification strategy. This strategy encouraged the use of renewable energy (RE), as an alternative to fossil fuel, and promoted biomass, biogas, municipal waste, solar and mini-hydro as RE resources. Under this plan, the government had set a target of 5% of the country's power generation mix from RE. However, this target has not been accomplished until now. Therefore, the 9th Malaysia Plan (2006–2010) was aimed at strengthening the previous plan by enhancing the use of RE and biomass resources from oil palm, wood, and rice-husk residue for the purpose of heat and electricity generation and biomass co-generation systems. It is expected that electricity generation from RE will reach 300 MW (Peninsular) and 50 MW (Sabah) by the end of the 9th Malaysia Plan (Energy Information Bureau, 2006). However, as of 2010, fossil fuel still predominates as the source of Malaysia's electricity generation – with RE contributing a mere 0.7%. This figure reveals that the government has failed to achieve the targets set. One of the key barriers is the poor cost-competitiveness of generating electricity from RE in comparison to conventional fossil fuels such as coal and NG. NG is more environmentally friendly compared to coal, and it continues to become the most promising fuel for electricity generation with Petronas currently subsidising up to 60% of Malaysia's NG price.

This scenario has encouraged the Malaysian government to introduce a new gas price structure with reduced subsidies. Under the new structure, the industrial

and power sectors are getting an 80% discount on the market price of gas starting from July 2008, and the discount will be gradually reduced until the gas price reflects the actual market price in 2022. This would lead to positive developments in terms of enhancing RE cost competitiveness. Besides, rising global concern for the environmental impact of fossil fuel utilisation is another major push for promoting the utilisation of RE resources. An econometric study has been conducted by Gan and Li (2008), and their projections under the reference scenario indicated that Malaysia's gross domestic product (GDP) is expected to average 4.6% from 2004 to 2030, and total primary energy consumption will triple by 2030. Coal imports will increase following the governmental policy of intensifying its use for power generation. Oil imports are predicted to take place by 2015 and reach 45 mtoe in 2030. Hence, Malaysia's energy import dependency will rise, and by using the same sources of fuel, carbon emissions will triple by 2030. On the other hand, their projections under an RE scenario showed that the utilisation of RE is a strategic option to improve the long-term energy security and environmental performance of Malaysia. However, substantial governmental involvement and support, as well as the establishment of a regulatory framework, is necessary.

Under the 10th Malaysia Plan, several new initiatives – anchored upon the Renewable Energy Policy and Action Plan – will be undertaken to achieve a renewable energy target of 985 MW by 2015, contributing 5.5% of Malaysia's total electricity generation mix, as shown in Figure 1.3. Amongst the measures taken will be:

i)   Introduction of a Feed-in Tariff (FiT) of 1% that will be incorporated into the electricity tariffs of consumers to support the development of RE. This mechanism allows electricity produced from RE to be sold to utilities at a fixed premium price and for a specific duration; and

ii)   Establishment of a Renewable Energy Fund from the FiT to be administered by a special agency, the Sustainable Energy Development Authority, under the Ministry of Energy, Green Technology and Water (KeTTHA) to support development of RE.
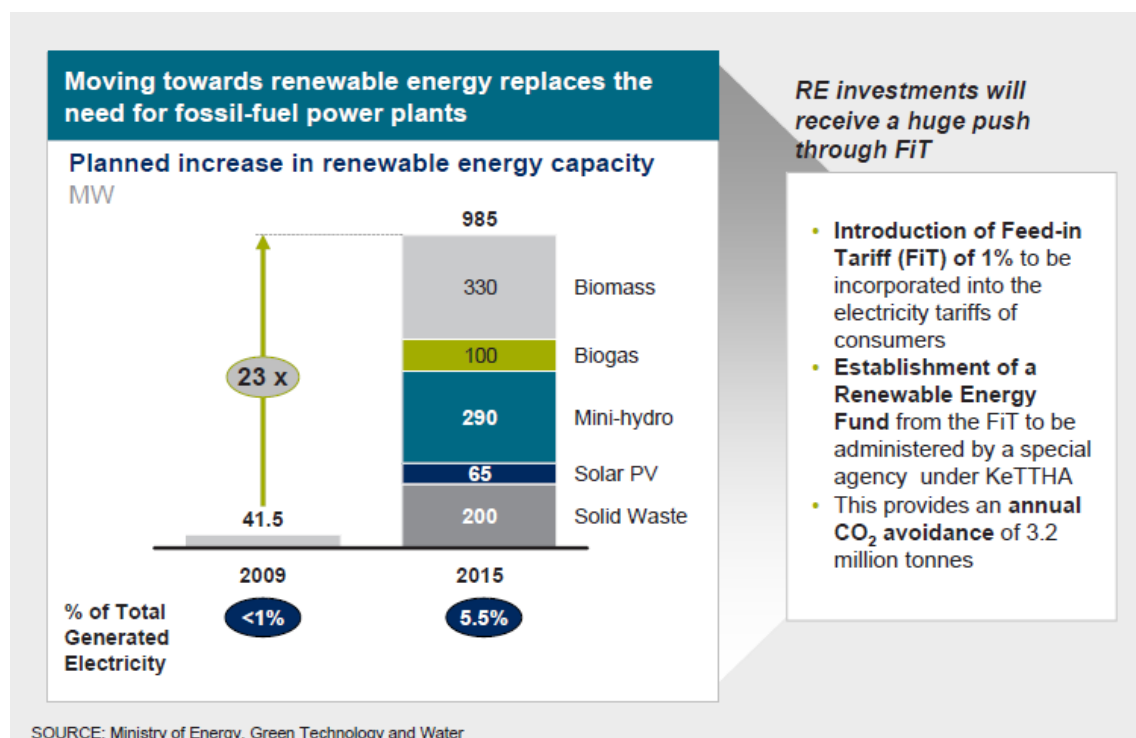
Figure 1.3 RE is expected to increase from <1% in 2009 to 5.5% of Malaysia's total electricity generated by 2015 (Ministry of Energy, Green Technology and Water, 2013)

1.1.1 Carbon Dioxide Emissions

Carbon dioxide (CO_2), methane, nitrous oxide (NOx) and sulphur oxide (SOx) emissions are categorised as greenhouse gases (GHGs) that are attributed to climate change. Rising concentrations of GHGs produce an increase in the average surface temperature of the earth over time. Rising temperatures may, in turn, produce changes in precipitation patterns, storm severity, and sea level – commonly referred to as "climate change".

The use of fossil fuels for energy production is the primary source increasing the concentration of CO_2 in the atmosphere. Energy use is largely driven by economic growth, as well as changes in the fuel used in electricity generation. Back in 1998, the United Nations Framework Convention on Climate Change already developed the Kyoto Protocol to stabilise the GHG emissions in the atmosphere by

having industrialised countries commit to reduce their GHG emissions. The legally binding accord was signed by 165 countries.

Southeast Asia collectively ranks third highest in GHGs emissions among developing countries, after China and India. Under the business-as-usual scenario of the International Energy Agency World Energy Outlook Projection, with 2003 as the base year, Southeast Asia's carbon dioxide emissions will increase by 350 per cent by 2050. This is an unacceptable scenario in the face of warnings issued by scientists about the direct consequences if the total global GHGs emissions are not cut to a half by the mid-century.

Among the Southeast-Asian countries, Malaysia is the highest emitter of CO_2. Even worse, Malaysia, which has rapidly transformed from an agricultural economy to an industrialised one in the last four decades, is now ranked as the 26th largest GHGs emitter in the world (International Herald Tribune, 2007). Carbon dioxide emissions in Malaysia increased by 21% between 2006 and 2010. Fossil fuels contributed to more than half of the total CO_2 increment. Figure 1.4 shows an increment of carbon emissions in Malaysia between 2006 and 2010 (IEA, 2011).
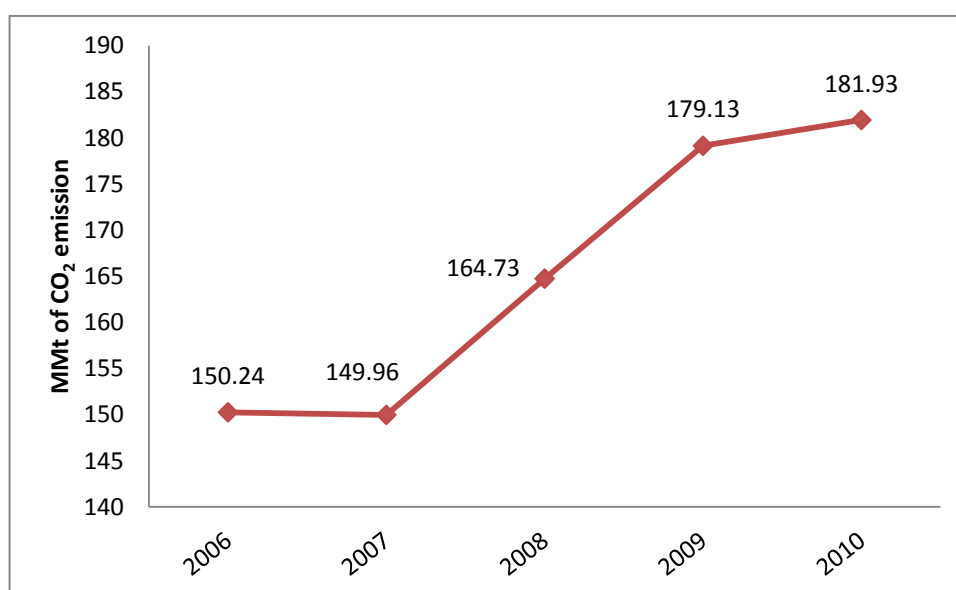
Figure 1.4   Carbon dioxide emissions in Malaysia from fossil fuel (IEA 2011).

During the Kyoto Protocol's first commitment period, developed-country signatories committed to reduce their GHGs emissions by 5.2 per cent from their 1990 levels within the period between 2008 and 2012. The signatories gathered in Bali, Indonesia, in December 2007, to negotiate the second phase of the agreement, covering the period between 2013 and 2017. Within this timeframe, industrialised countries need to reduce their CO_2 emissions by 18 per cent from 1990 levels, and then by 30 per cent between 2018 and 2022, with a target of a 75 per cent reduction by the mid-century. Only with these cuts is there a reasonable chance of keeping the average increase in global temperatures to less than 2°C – beyond which the effects of climate change will become catastrophic. During the United Nations Climate Change Conference, 2009 (COP 15), in Copenhagen, Prime Minister Datuk Seri Najib Tun Razak announced that Malaysia has agreed to reduce its carbon dioxide emissions by up to 40 per cent by 2020 compared with its 2005 level.

Malaysia contributes only 0.7% to global CO_2 emissions based on the UNDP Human Development Report 2007/2008. However, on an emission-intensity levels basis, calculated as a ratio of GHGs emissions to the country's GDP, Malaysia's emission-intensity levels are above the global average in the energy sector, as shown in Figure 1.5. In the 10th Malaysia Plan, major efforts will be introduced to reduce emission intensity. As Malaysia moves towards a high-income economy, its emission intensity is expected to decline.

The government has embarked on several programmes aimed at reducing emissions of GHGs. During the planned period, these efforts will continue to focus on five areas:

i)   Creating stronger incentives for investments in renewable energy (RE);

ii)   Promoting energy efficiency to encourage the efficient use of energy;

iii)   Improving solid waste management;

iv)   Conserving forests; and

v)   Reducing emissions to improve the air quality.
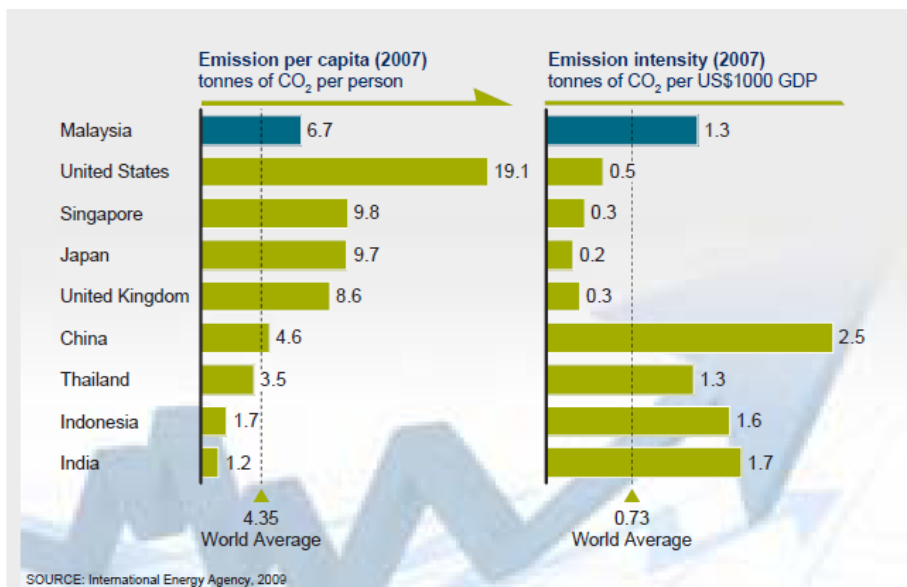
Figure 1.5 Malaysia's emission intensity was higher than the global average for energy sector in 2007 (International Energy Agency, 2009)

1.1.2 Renewable Energy Potential in Malaysia

Malaysia's potential for RE generation is substantial. Its equatorial location is superb for harnessing solar energy, and its extensive tropical forests can supply large quantities of biomass. Hydropower already plays a significant part in the nation's energy mix, particularly on the island of Borneo, and mini-hydropower from streams and rivers has boosted the electricity supply in rural areas. Municipal solid waste is also as an option for energy generation in Malaysia.

As one of the largest palm-oil producers in the world, there is an abundance of resources of palm-oil residues that can be utilised to generate electricity. Other sources, such as paddy and wood-processing residues, municipal waste and landfill gas, can be used for electricity generation. Malaysia has abundant hydropower potential with a total potential capacity of 29 GW (with 70% in Sarawak) (Meteorological Department of Malaysia, 2009). Only 2.119 GW has been tapped so far: 1.191 GW from Peninsular Malaysia and the rest from Sabah and Sarawak (Energy Commission, 2010).

Utilisation of biomass, especially oil palm, has been investigated through several pieces of research (Sumathi *et al*., 2008; Wicke *et al*., 2008). Palm oil not only can be used as a source of edible oil but can also be enhanced into excellent RE. Biomass can be converted to electricity through several processes: direct-fired, gasification, anaerobic digestion, pyrolysis and small modular systems (Sumathi *et al*., 2008). Oil palm biomass is one of the promising RE resources in Malaysia and can act as an example to other countries in the world that have huge biomass feedstocks (Shuit *et al*., 2009).

High and volatile natural gas prices have increasingly led to calls for investments in RE. Evaluating studies and benchmarking several findings against economic theory, other modelling results, and a limited empirical literature, Wiser and Bolinger (2007) found that many uncertainties remain regarding the absolute magnitude of this effect, and that the reduction in natural gas prices may not represent an increase in aggregate economic wealth. They conclude that many of the studies of the impact of RE on natural gas prices appear to have represented this effect within reason – given the current knowledge. These studies specifically suggest that a 1% reduction in US natural gas demand could lead to long-term average wellhead price reductions of 0.8–2%, and that each megawatt-hour of renewable energy may benefit natural gas consumers to the tune of at least $7.5–20 (Wiser & Bolinger, 2007).

Biomass can be considered as the best option and has the largest potential to meet these requirements and could ensure fuel supply in the future. The modernisation of biomass technologies, leading to more efficient biomass production and conversion, is one possible direction for biomass use in developing countries. It is critical, therefore, that the biomass processes used in developing countries are sustainable.

In industrialised countries, the main biomass processes utilised in the future are expected to be the direct combustion of residues and wastes for electricity generation, ethanol and biodiesel as liquid fuels, and combined heat and power production from energy crops. The future of biomass electricity generation lies in

biomass integrated gasification / gas turbine technology, which offers high energy conversion efficiencies (Wiser *et al*, 2004).

Utilisation of biomass resources will be one of the most important factors for environmental protection in the 21st century. Biomass absorbs CO_2 during growth, and emits it during combustion. Therefore, biomass helps the atmospheric CO_2 recycling and does not contribute to the greenhouse effect. Biomass consumes the same amount of CO_2 from the atmosphere during growth as is released during combustion. In addition, overall CO_2 emissions can be reduced because biomass is a CO_2 neutral fuel (Demirbas *et al*., 2009).

Currently, more than 80% of the world's biodiesel production is from rapeseed oil. However, the cost of palm oil, which is at least US$200 per tonne cheaper than rapeseed oil, indicates that palm oil could be a more suitable and attractive candidate as the source of biodiesel compared to other vegetable oils. Palm oil is known to be a multi-purpose vegetable oil with products ranging from food to biodiesel (Tan *et al*., 2009).

1.2   Problem Statement

In Malaysia, the efforts and developments to mitigate issues of security, energy efficiency and environmental impact have been on-going since 30 years ago. The Malaysian government has developed key policies and strategies to achieve the nation's aims.

In the context of RE, during the 8th Malaysia Plan (8MP – 2001–2005), the five-fuel strategy was introduced to promote the use of RE as well as to address rising global concern for climate change. A year after the introduction of the five-fuel policy, the Small Renewable Energy Power (SREP) programme was launched in May 2001, and in order to ensure the development during 8MP, the Biomass Generation and Demonstration (BioGen) Project was then launched (Mustapa *et al.*,

2010). Under the 9th Malaysia Plan (9MP – 2006–2010) the National Biofuel Policy (2006) and the National Green Technology Policy (2009) were launched in an effort to promote RE resources. Additionally, two other RE programmes were also launched under the 9MP: Malaysia Building Integrated Photovoltaic (MBIPV) and Centre for Education and Training in Renewable Energy and Energy Efficiency (CETREE). MBIPV is mainly for solar energy developments while CETREE's main target is to increase the public's awareness of the importance of RE through education and training. However, RE projects in Malaysia only achieved a capacity of 56.7 MW out of the targeted 350 MW by the end of the 9MP.

Subsequently, the National Renewable Energy Policy (2010) was launched under the 10th Malaysia Plan (10MP), with a new target of achieving 985 MW of power capacity consisting of RE by 2015. Therefore, electricity power planning to achieve the said targets is highly needed. Yet, electricity power capacity expansion planning is highly complicated, involving a large number of technologies, technological constraints, intermittent resources, weather variability, and fuel-price fluctuation, coupled with complex temporal and spatial variability. Previously, Hashim (2006) developed an MINLP model for electricity generation in Ontario, Canada. The model then had to be linearised to MILP. However, time index has not been addressed in her work. The most recent research related to this work has been done by Mirzaesmaeli (2007). He extended Hashim's (2006) work and developed a multi-period deterministic model for electricity capacity expansion planning in Ontario, Canada. However, RE for intermittent and non-intermittent resources, such as solar, wind, hydro and biomass, has not been taken into consideration. In addition, the selection of optimal locations for new plant construction will be considered in this model.

This study is therefore conducted to develop cost optimal multi-period electricity planning modelling to fulfill forecasted electricity demand for a specified time horizon as well as to ensure that RE and CO_2 intensity reduction targets can be met. This model is also able to determine locations for building new RE power plants. Note that this model can be applied to any location in the world.

1.3   Objectives of the Study

The main objective of this research is to develop a multi-period mixed integer linear programming (MILP) model with considerations of emission reduction.

1. To design and optimise the cost-optimal integrated energy system, i.e. capacity and type of technologies, comprising both fossil fuel and RE sources.

2. To determine the optimal energy mix from available options, fossil fuel and RE for fleet-wide Peninsular Malaysia and a region (Iskandar Malaysia) with the implementation of CO_2 mitigation strategies.

3. To propose optimal electricity system power planning over a period of 13 years (from 2013 to 2025) towards fulfilling the forecasted electricity demand and simultaneously meeting the emissions reduction target.

4. To determine the optimal location for construction and operation of new biomass power plants to reduce transmission losses and transportation costs.

1.4   Scope of the Study

To achieve the intended research objective, the scope of work has been drawn as follow:

1.   Collection of data from Peninsular Malaysia and Iskandar Malaysia (IM) on the average annual energy demand (includes the increment over the 15 years), availability of RE sources, RE implementation targets, CO_2 reduction targets, solar intensity of the five flagships of IM, location of substation, distribution line distances and suitable location for power-plant development.

2.   Collection of data on the forecasted cost of various power plants (capital cost, fixed operating and maintenance cost, and variable operating and

maintenance cost) and forecasted fuel price (coal, oil, natural gas, and biomass).

3. Design of an integrated energy system consisting of commercial sources (fossil fuel as centralised generation) and RE sources (solar, biomass, biogas, and mini-hydro as decentralised generation).

4. Formulation of a mathematical model for electricity capacity planning for an integrated system that minimises the overall cost of the power-generation system and simultaneously satisfies various constraints (forecasted energy demand, RE target, and CO_2 emission-reduction target).

5. Coding of mathematical model in GAMS.

6. Perform sensitivity analysis on the model by changing various inputs, i.e. CO_2 emission reduction (0 to 40 per cent reduction) and natural gas price fluctuation.

7. Applying the optimisation model to Peninsular Malaysia and Iskandar Malaysia.

1.5 Research Contributions

The key specific contributions of this work are summarised as follows:

1) A new single period optimisationoptimisation model for electricity capacity planning, comprising existing power plant (fossil and non-fossil fuel) and new power plant (fossil and RE) for Peninsular Malaysia with the target of reducing CO_2 emissions at the minimum cost:
− A generic mixed integer linear programming (MILP) model has been developed based on superstructure to simultaneously set the targets.
− The model was tested to observe natural gas price fluctuation.

2) A new multi-period optimisation model for electricity capacity planning, comprising existing power plant (fossil and non-fossil fuel) and new power plant (fossil and RE) for Iskandar Malaysia with the target of reducing CO_2 emissions at the minimum cost:

− A generic mixed integer linear programming (MILP) model has been developed based on superstructure to simultaneously set the targets.

− The model includes time index, construction lead time and electricity generation for peak and off-peak. It can predict capacity building and generation for 13 years.

3) A new multi-period optimisation model to select the best location to build new RE power plant in Iskandar Malaysia:

− A new generic optimisation model is able to select the best location with different capacity and type of technologies with the target to minimise the capital cost, transmission lost and transportation cost.

4) The optimisation model is generic, and can therefore be employed to any case study.

5) The optimisation model can be applied to a wide range of fuel sources, not only fossil fuel or biomass.

Appendix A lists all the publications and output of this work and the associated key contributions of this thesis towards global knowledge on electricity planning.

1.6 Summary of the Thesis

This thesis consists of six chapters. Chapter 1 is an overview of the electricity generation issues, problem background, problem statement, objectives and scope of the research, which aims to develop a new electricity-generation model for electricity planning using the mathematical approach. Chapter 2 describes the fundamental theory and relevant literature review related to electricity planning, generation and its environmental impact. Chapter 3 represents an overview of methodology of this

study to achieve the targeted objectives. Chapter 4 represents a detailed methodology, model, results and discussion for single-period electricity planning using Peninsular Malaysia as a case study. Chapter 5 describes a detailed methodology, model, results and discussion for multi-period electricity planning in Iskandar Malaysia. Chapter 6 represents a detailed methodology, model, results and discussion for multi-period RE electricity planning in Iskandar Malaysia. Finally, Chapter 7 concludes the key contributions of this research, prior to the recommendation of possible future work.

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