CARBON-CONSTRAINED ENERGY PLANNING FOR INTEGRATED TRANSPORTATION AND POWER GENERATION SECTORS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

FEBRUARY 2021

ACKNOWLEDGEMENT

Alhamdulillah, all praise be to Allah The Al-Mighty. I wish to express my gratitude to my supervisors, Dr. Zarina Ab Muis and Dr. Ho Wai Shin, for their strong support, constant comments, suggestion, guidance, and encouragement throughout this work. May all your contributions be paid off with blessings from the merciful Allah Azzawajalla.

Grateful appreciation to PROSPECT student and staff for their support. The hardship I encountered was certainly more or less lightened by the aid offered. I would also like to acknowledge Universiti Teknologi Malaysia, not only for their financial support, but also for all other assistances to facilitate my study.

Special thanks to MyBrain for awarding me sponsorship to conduct this study. It is indeed much needed help considering my financial situation.

Last but not least, I dedicate a mountain of love and appreciation to my parents, my family and Noor Nurul Fatihah Binti Che Othman for their encouragement and moral support and doa. May Allah AWJ reward all of you here and in the hereafter.

ABSTRACT

The introduction of electric vehicles (EV) has changed the transportation and power generation systems, mainly affecting energy production, energy efficiency, and overall grid performance. In Malaysia, the government stated its commitment to adopt green initiatives and sustainable development. Thus, this research presents the energy planning framework for power generation and transportation system which determines the optimal energy mix by utilizing available renewable energy resources and the best location for charging stations. This research utilized carbon emission pinch analysis (CEPA) as a baseline model to conduct a feasibility study for electric vehicles in Malaysia. Mathematical equations were then applied to develop a mixed-integer linear programming model incorporated complex constraints for further holistic analysis of Malaysia. Four scenarios were devised to explore the impact of different carbon emission mitigation strategies. The results show that Scenario 4 (S4), which considered 40 % of total carbon emission reduction come from transportation sector, provide the best option in terms of energy mix, technology selection, levelized cost of electricity, and operation of EV. Although it requires the highest number of EV on the road compared to other scenario which is 2,345,776 units, it will only utilize 66,260.61 GWh of energy to be generated from renewable energy which is the lowest compared to the other scenarios. This results in the lowest levelized cost of electricity which is 0.3364 RM/kWh. This tariff can be applied to lower the cost of charging for EV operation. This research also provides strategies for the government to implement electric vehicles in Malaysia. The models may also be converted into useful software for town planners and policymakers.

ABSTRAK

Pengenalan kenderaan elektrik (EV) telah merubah sistem pengangkutan dan sistem penjanaan kuasa dari segi pengeluaran tenaga, kecekapan tenaga, dan prestasi grid secara keseluruhan. Di Malaysia, kerajaan telah menyatakan komitmen ke arah inisiatif hijau dan pembangunan mampan. Oleh itu, penyelidikan ini membentangkan kerangka perancangan tenaga untuk penjanaan tenaga dan sistem pengangkutan untuk menentukan campuran tenaga optima dengan penggunaan sumber tenaga yang boleh diperbaharui dan menentukan lokasi yang terbaik untuk stesen pengecasan kenderaan elektrik. Kajian ini menggunakan teknik analisa jepit pelepasan karbon (CEPA) sebagai penanda aras untuk melakukan kajian keupayaan pelaksanaan EV di Malaysia. Persamaan matematik kemudiannya digunapakai dengan membangunkan model pengaturcaraan linear integer bercampur yang menggabungkan kekangan kompleks untuk analisa holistik lebih lanjut di Malaysia. Empat scenario telah dirangka untuk mengkaji kesan perbezaan strategi pengurangan pelepasan karbon. Hasilnya menunjukkan bahawa Scenario 4 (S4), yang melibatkan 40 % daripada jumlah pengurangan pelepasan karbon adalah daripada sektor pengangkutan, menunjukan pilihan yang terbaik dari segi campuran tenaga, pemilihan teknologi, tarif, dan operasi EV. Walaupun scenario ini memerlukan jumlah EV paling tinggi di jalan raya berbanding dengan senario lain iaitu 2,345,776 unit, ia hanya menggunakan 66,260,61 GWh tenaga yang perlu dihasilkan dari tenaga boleh baharu yang merupakan yang terendah berbanding dengan senario lain. Ini memberikan kos elektrik paling rendah iaitu 0.3364 RM / kWh. Tarif ini boleh digunakan untuk menurunkan kos pengecasan untuk operasi EV. Penyelidikan ini juga memberi strategi kepada pemerintah untuk melaksanakan kenderaan elektrik di Malaysia. Model-model tersebut boleh diubah menjadi perisian yang berguna untuk perancang bandar dan pembuat dasar.

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LIST OF ABBREVIATIONS

GHG	-	Greenhouse gas
CO_2	-	Carbon dioxide
RE	-	Renewable energy
ICEV	-	Internal Combustion Engine Vehicle
EV	-	Electric vehicle
MILP	-	Mixed-integer linear programming
NG	-	Natural gas
IGCC	-	Integrated Gasification Combined Cycle
PHEV	-	Plug-In Hybrid Electric Vehicle
HEV	-	Hybrid Electric Vehicle
BEV	-	Battery Electric Vehicle
FCEV	-	Fuel Cell Electric Vehicle
V2G	-	Vehicle-to-grid
AC	-	Alternating current
DC	-	Direct current
TCO	-	Total cost ownership
PoPA	-	Power pinch analysis
ESCA	-	Electric system cascade analysis
SAHPPA	-	Stand-alone hybrid power plant analysis
P-PoPA	-	Probability power pinch analysis
CEPA	-	Carbon emission pinch analysis
CCS	-	Carbon capture and storage
EROI	-	Energy return on energy investment
WAMPA	-	Waste management pinch analysis
GAMS	-	General algebraic modelling system
AIMMS	-	Advanced interactive multidimensional modelling system
COIN-OR	-	Computational infrastructure for operation researches
SCIP	-	Solving constraint integer programs
AMPL	-	A mathematical programming language
BPKM	-	Billion passenger kilometer

PC	-	Pulverized coal
OCGT	-	Open Cycle Gas Turbine
CCGT	-	Combined Cycle Gas Turbine
PV	-	Photovoltaic
CHP	-	Combined heat and power
O&M	-	Operating and maintenance
COE	-	Cost of electricity
LCOE	-	Levelized cost of electricity
TNB	-	Tenaga Nasional Berhad
NO_x	-	Nitrogen oxide
SO_x	-	Sulfur oxide

LIST OF SYMBOLS

TD	-	Total travel demand
NV	-	No. of vehicle units
DT	-	Average distance travelled
O	-	Occupancy level
ETF	-	Transport fuel emission factor
EF	-	Fuel emission factor
VE	-	Vehicle efficiency
OR	-	Occupancy ratio

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CHAPTER 1

INTRODUCTION

1.1 Climate Issue and Emission Trends

According to Churchill (2017), climate change and energy security are the major concerns related to global warming. As the consequences of global warming, the global temperature has increased to the range of 0.55 °C–0.80 °C since 1986 up to 2005. However, 2015 was the first year the change rose to more than 1 °C. This scenario was mainly due to human activity starting from the Industrial Revolution, which increased the amount of greenhouse gas (GHG) released to the atmosphere (Hawkins *et al*., 2017).

Carbon dioxide (CO_2) is the main component in GHG emission that causes the rise in global temperature. CO_2 is usually produced from the burning of fossil fuels. Global carbon emissions have increased tremendously over the past half-century. This increased CO_2 emissions may lead to serious health complications. A previous study by Shindell *et al.* (2018) found that the reduction in CO_2 could help lead to 153 million fewer premature deaths worldwide. According to a report by the International Energy Agency (2018a), global CO_2 emissions from fuel combustion were 32.31 Gt-CO_2 in 2016, broadly similar to the statistics in 2015 (32.28 Gt-CO_2). However, this number has doubled since the early seventies and has increased by around 40% since 2000, as shown in Figure 1.1. The emissions exceeded 32 Gt-CO_2 in 2013 and then stabilized for the following three consecutive years (2013–2016).

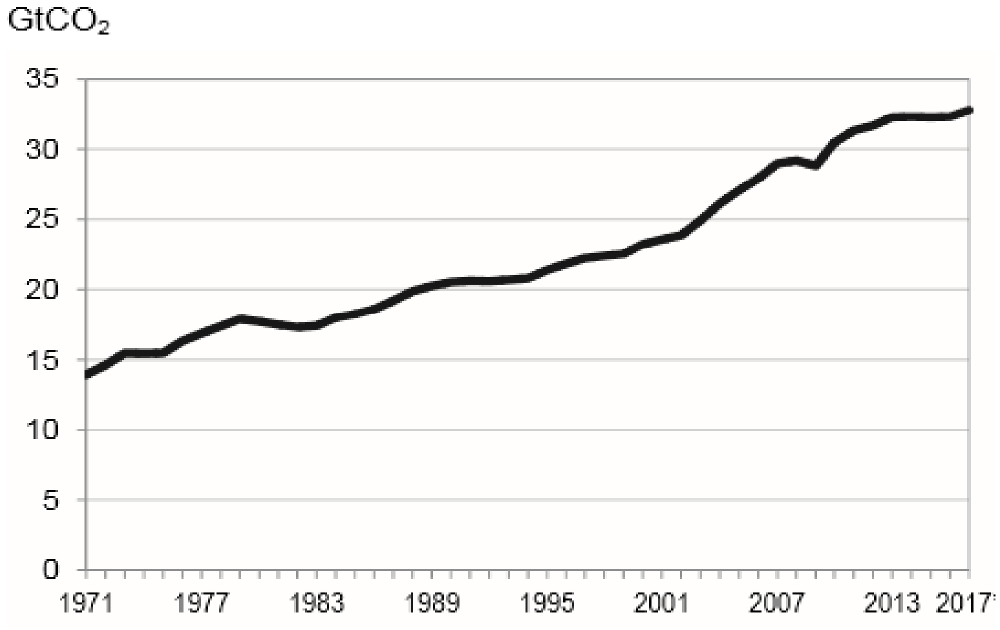

Figure 1.1 CO_2 emissions from fuel combustion: global trend (International Energy Agency, 2018a)

A report published by the International Energy Agency (2018b) highlighted the breakdown of global CO_2 emissions by sector, as shown in Figure 1.2. The decrease in emissions for the industrial sector (2.3%) offset the increase in electricity and heat generation, transport, and building sectors together in the year 2016. The power generation and transportation sectors are the key contributors to global warming since these two sectors are the main energy consumer sectors compared to the others. The dependency on fossil fuels such as coal and natural gas for electricity generation in power generation, as well as petrol and diesel in the transportation sector, has led to increased CO_2 production.

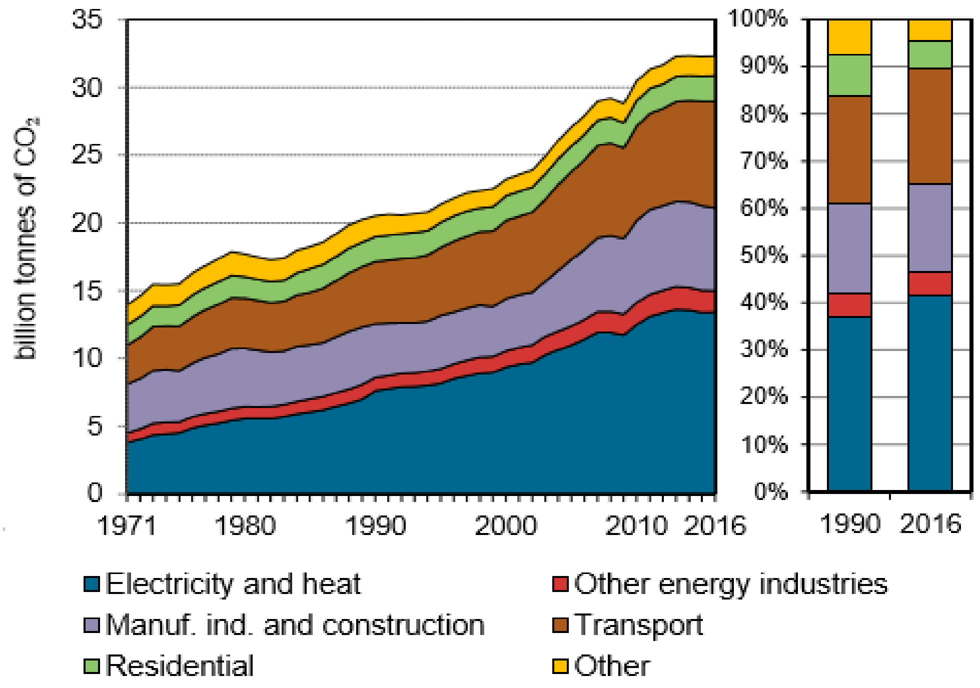

Figure 1.2 Global CO_2 emissions by sector (International Energy Agency, 2018b)

As a solution to global warming, research on renewable energy (RE) has now gained increasing popularity. Bhattacharya *et al.* (2017) found that RE consumption significantly impacted economic output and CO_2 emission. In the power generation sector, many alternatives have been proposed to adopt green initiatives. The currently available RE resources for electricity generation are solar energy, wind energy, hydro energy, tidal energy, and nuclear energy. On the other hand, for the transportation sector, some alternative fuels to replace conventional fuel (petrol and diesel) have been developed. These efforts started with the introduction of biofuels for internal combustion engine vehicles (ICEVs). However, some issues related to these fuel sources have emerged, as this type of fuel depends on the availability of biomass resources. In addition, the production of these fuels such as the hydrogen fuel cell is not very practical due to safety issues such as high flammability.

Global climate and energy security concerns have led to the electrification of road transportation. The development of electric vehicle (EV) technology has shown promising results. According to Kester *et al.* (2018), EV has become an important instrument and solution to decarbonize the transportation sector, as it offers several benefits such as reduced local pollution, reduced noise emissions, and reduced oil dependency. Moreover, EV basically has fewer mechanical parts and a simpler configuration compared to conventional vehicles and therefore provides lower maintenance costs. Additionally, EVs have higher energy efficiency compared to ICEVs. The only issue is that EVs have a higher purchase price than ICEVs.

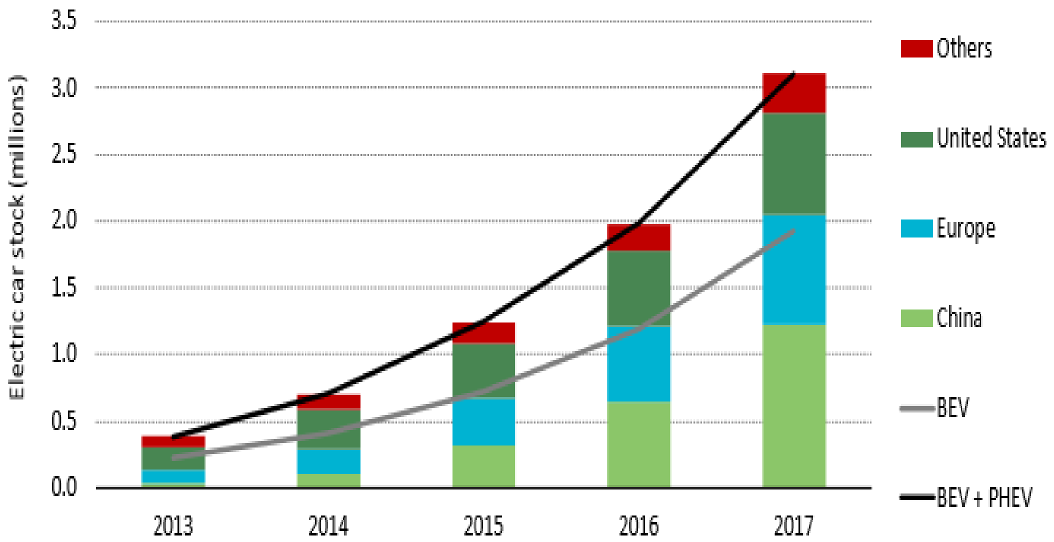

Figure 1.3 Evolution of the global electric car stock, 2013–2017 (International Energy Agency, 2018c)

A report from the International Energy Agency (2018c) highlighted that the global stock of electric cars had surpassed 3 million vehicles in 2017 after crossing the 1 million-threshold in 2015 and the 2 million mark in 2016. The figure has further increased by 56% compared to 2016, as shown in Figure 1.3. In 2017, China recorded the largest electric car stock: 40% of the global total. In 2017, the stock of electric buses increased to 370,000 units and electric two-wheelers reached 250 million. The electrification of these modes has been driven mostly by developments in China, which accounts for more than 99% of both electric bus and two-wheeler stocks, although registrations in Europe and India are also on the upswing.

1.1.1 The Electric Vehicle Roadmap in Malaysia

Figure 1.4 shows the project timeline for a greener transportation sector by 2030. As outlined in the National Automotive Policy (NAP), the effort towards encouraging the development of EV should be continued. While waiting for the EV ecosystem to mature, technology on improving the efficiency of existing internal combustion engine (ICE) based vehicles should be developed (MITI, 2020). Given the current technological development, electrification of transportation is an inevitable trend. EVs offers zero tailpipe emissions and the highest energy efficiency amongst all other modes. According to a report published by KeTTHA (2017), NAP is focusing on local manufacturing and the local manufacturing requires technology acceptance to reach the mass market; hence reaching viable volume for local manufacturing operation. To ride on this tide of EV development, it is crucial for Malaysia to embark on electric vehicle technology development. The core technologies in EV include electric motor design, power electronics converters, energy storage systems and battery charging technology.

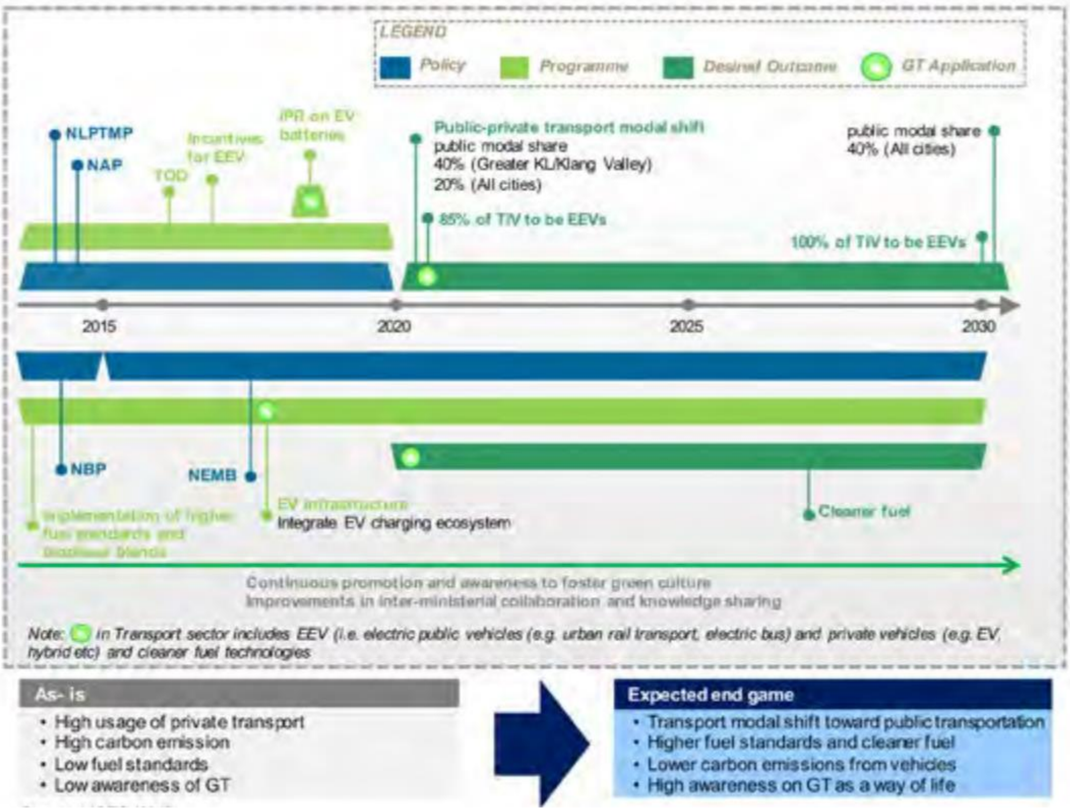

Figure 1.4 Timeline for transport sector (KeTTHA, 2017)

A report published by GreenTech Malaysia (2019) had highlighted several actions that already been done to achieve these goals. In 2016, Tesla programme had been initiated in order to provide access to Malaysian on the latest EV technology in the world. The Government granted GreenTech Malaysia RM5 million for the first phase of rolling out EV charging points across Malaysia, which entailed the installation of 200 charging points in the Peninsular. MGTC introduced ChargEV, its public EV charging station network brand. The charging station infrastructure also serves as an instrument for the public to experience an EV lifestyle. With the collaboration of Sarawak Energy Berhad, ChargEV has now reached East Malaysia, where four stations have been set up in Kuching. As of December 2019, the network of ChargEV stations in the country comprised 300 units.

1.2 Problem Statement

Recently, the government of Malaysia has pledged to achieve a carbon emissions reduction by 45 % in the year 2030 (MITI, 2017). To achieve this target, numerous initiatives have been planned to meet several environmental criteria such as increased renewable energy (RE) share in the energy mix in the power generation sector. However, the transportation sector also plays a huge role in carbon emission production and not just for power generation alone. The government has taken an initiative to promote the use of electric vehicles (EVs) in Malaysia. The government now targets 100,000 EVs to be on the road and 125,000 units of charging stations to be installed by 2030 (GreenTech Malaysia, 2015).

This large-scale implementation of EV will cause the power generation sector to generate more electricity. In addition, an EV will only give its full benefit if the electricity used to run the EV is generated using low-carbon fuel sources or zero-carbon fuel sources. With the high electricity demand due to EV and its driving range limitation due to the battery size of the EV, the charging stations must be installed to ensure that the EV can be charged anywhere within any distance range. Recent study by Kikusato *et al.* (2019) had explored the charging and discharging behaviour for EV. However, the model proposed only limited to small scale EV system which is residential operation of solar PV. A larger model required to simulate the energy planning for large-scale EV implementation.

The optimization technique is a suitable approach for energy planning. A few studied have been done focus on the impact of EV towards power generation sector. However, these previous works mostly focus on the energy management from supply and demand side (Wu *et al.,* 2019); and scheduling of EV (Liu *et al.,* 2018). The previous optimization model developed lack in presenting the impact of different mitigation strategies in term of carbon emission target, EV penetration rate towards both power generation and transportation sector, and the impact towards electricity tariff. Thus, this study was proposed to address the limitation by exploring the impact of EV implementation based on different carbon emission reduction strategy towards energy mix, technology selection, electricity tariff, operation of EV, and infrastructure (EV charging station) planning.

1.3 Objectives of the Study

Based on the problem statement, the main purpose of this work is to develop an overall energy planning system based on a mixed-integer linear programming model for power generation sector and transportation (EV) system. The sub-objectives covered in this study are as follows:

(a) To determine the minimum amount of EV required using the pinch analysis technique as a baseline model.

(b) To investigate the optimal energy mix (fossil fuel and non-fossil fuel) for an energy system comprising electricity demand involving EV.

(c) To propose an optimal location for the charging station based on the EV operations and routes.

(d) To demonstrate and assess the proposed strategies based on their economic and environmental impacts.

1.4 Scope of the Study

This study focuses on the development of a mixed-integer linear programming (MILP) model. The model developed comprises two types: a graphical model and a mathematical model. This study also emphasizes energy planning based on the macro level. The scope of this work is illustrated below:

(a) Developing a graphical model based on the pinch analysis technique for the transportation sector. The model comprises a transportation mode and fuel sources. The transportation mode mainly covers passenger-type vehicles, namely trains, buses, cars, and motorcycles. The fuel sources include fossil fuel (petrol, diesel, natural gas) and non-fossil fuel (biofuel, electricity).

(b) Developing an energy mix model that considers fossil fuel and non-fossil fuel sources. Developing an energy mix model based on the MILP model comprising several technologies including Pulverized Coal, Open Cycle Gas Turbines, Combined Cycle Gas Turbines, Solar Photovoltaic cells, Hydro turbines, and biomass technologies. The model also enables the selection process of whether to build a new power plant to meet the electricity demand. The model aims to minimize the total cost (capital cost and operating and maintenance cost) of the power system with carbon emission constraints.

(c) Developing a location model for EV bus charging stations. The model is illustrated using the route and charging schedule of the EV bus. The model is integrated with centralized energy generation running on renewable energy such as solar energy and biomass resources. Other parameters such as geographic location, distance, traffic condition, and resource availability are also considered in this model.

(d) An environmental and economic assessment is conducted. A sensitivity analysis is done by proposing different scenarios for each developed model. The analysis is based on different proposed policies, different emissions targets, and different numbers of implemented EVs. The environmental assessment covered different emission strategy by varying percent emission reduction for both transportation and power generation sector. Meanwhile, economic assessment includes the different levelized cost of electricity implementation.

1.5 Significance of the Study

This project provides a medium-term strategy leading up to 2030 together with a quantified assessment of the optimal energy mix and best technology selection for power generation, energy storage, and the best time to charge and discharge an electric vehicle (EV). It also provides the optimal location to install new charging stations for EVs. A case study was done to demonstrate and deliver an integrated infrastructure strategy and plan for Iskandar Malaysia, but a novel methodology is also developed that is generally applicable to any case study. The research outcomes are delivered through conferences, publications such as journal papers, focus group discussions, and workshops. Throughout this research work, several key contributions were achieved:

(a) The pinch analysis application includes the sequential work from transportation to power generation sector to show the relation from both sector in term of emission, energy mix, and technology selection. The framework developed and can be used as an early planning strategy for the government, town planners, and policymakers.

(b) The mathematical model developed can determine the optimal fuel mix based on fossil fuel and non-fossil fuel, the best technology selection for transportation and power generation sector, and a suitable time to implement renewable energy technologies.

(c) The result of the model will help in the development of Iskandar Malaysia to achieve its target as a "Low-Carbon City" by the year 2030.

(d) The developed model is generic and applicable to any case study. Besides, the model can further be developed and transform into useful software.

(e) The results obtained from the model could improve the air quality in Malaysia and provide a cleaner road environment for urban areas.

1.6 Summary

As a conclusion to the introduction section, this thesis extends to up to seven chapters. Chapter 1 provides the research area and sets the goals that must be achieved to solve the research problem in which case a mathematical approach is applied. Chapter 2 provides a detailed review of the state-of-the-art and the fundamentals of a power generation and transportation system. It also provides a better understanding of the technologies and resources available for both sectors in Malaysia. Chapter 3 then describes the overall flow of the thesis in terms of graphical analysis and mathematical modeling. Chapters 4, 5, and 6 present the development of optimization models, as well as their application via a case study that includes results and discussion. Chapter 4 technically presents the application of a graphical technique and discusses the potential policies that the government could apply for transportation sectors towards a greener initiative. Chapters 5 and 6 specifically discuss the mixed-integer linear programming approach to the system that integrates the power generation and transportation sectors. Chapter 5 focuses on the energy mix and technology selection for power plants involving EV while Chapter 6 focuses on an optimal location for EV charging stations. Finally, Chapter 7 provides a summary of all the findings of this research and proposes some directions for future works.

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