QUANTIFICATION OF POTENTIAL ENVIRONMENTAL IMPACTS OF ELECTRICITY GENERATION FROM THE WOOD WASTES USING LIFE CYCLE ASSESSMENT APPROACH

CHOONG JOO EE

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019
QUANTIFICATION OF POTENTIAL ENVIRONMENTAL IMPACTS OF ELECTRICITY GENERATION FROM THE WOOD WASTES USING LIFE CYCLE ASSESSMENT APPROACH

CHOONG JOO EE

DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING UNIVERSITY OF MALAYA KUALA LUMPUR

2019
UNIVERSITY OF MALAYA
ORIGINAL LITERARY WORK DECLARATION

Name of Candidate:  
(I.C/Passport No:  )
Matric No:
Name of Degree:
Field of Study:

I do solemnly and sincerely declare that:
(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya (“UM”), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate’s Signature  
Date:

Subscribed and solemnly declared before,

Witness’s Signature  
Date:

Name:
Designation:
ABSTRACT

Waste-to-Energy technology emerged as a sustainable approach for solid waste management. It converts waste into energy in form of heat and electricity. However, implementation of WtE technology in Malaysia, a developing country is still very limited due to various factors. In order to quantify potential environmental impacts of electricity generation from wood wastes, life cycle assessment (LCA) methodology was used to evaluate the environmental impacts for a WtE plant which was currently involved in feed-in tariff (FiT) mechanism introduced by government under biomass-solid waste category located at Rasa, Selangor. Life cycle analysis of the biomass-fired power plant which utilized wood waste from industrial, commercial and institution (ICI) as fuel of 7 MW capacity was done covering various environmental impacts using SimaPro software. ReCiPe Midpoint (H) method was chosen for the assessment. The LCA results that showed environmental impacts for the plant in producing 1 kWh of electricity were compared to current national grid. The results showed a total contribution of 0.319 kg CO\(_2\) eq of greenhouse gas (GHG) was emitted for every kWh of electricity generated by the biomass-fired power plant based on climate change factor in the LCA analysis. The emission factor is 96.1% lower than the electricity generated by conventional power plant which is 0.82 kg CO\(_2\) eq of GHG emission in Malaysia. The biomass-fired power plant would produce lesser impacts to environment than national grid for every kWh of electricity generation in term of photochemical oxidant formation, particulate matter formation, human toxicity, terrestrial acidification, marine eutrophication, freshwater eco-toxicity, fossil depletion, metal depletion and water depletion. A scenario was created to show the relationship between the percentages of carbon emissions reduction that is in line with Malaysia's commitment to reduce GHG emissions by up to 45% by 2030, hence making the utilization of biomass and solid waste as a reliable source of renewable energy as targeted by SEDA Malaysia. In conclusion, WtE technology could simultaneously dispose solid waste, reduce GHG emissions and increase share of RE in Malaysia’s electricity mix.
Teknologi waste-to-energy muncul sebagai pendekatan mampun dalam pengurusan sisa pepejal. Ia mampu menekan sisa pepejal kepada tenaga dalam bentuk haba dan elektrik. Namun, penggunaan teknologi WtE di Malaysia, sebuah negara yang sedang membangun ternyata masih terhad dibebani oleh beberapa faktor. Bagi mengkaji impak penjanaan kuasa elektrik melalui sisa kayu, metodologi penilaian kitaran hayat digunakan untuk menilai impak operasi sebuah loji WtE yang terletak di Rasa, Selangor terhadap alam sekitar. Loji WtE tersebut merupakan satu-satunya loji WtE yang tersenarai bawah kategori biojisim-sisa pepejal dalam mekanisme FiT yang diperkenalkan oleh kerajaan bagi menggalakkan penggunaan tenaga boleh diperbaharui.

Analisa kitaran hayat terhadap loji janakuasa biojisim berkapsiti 7 MW yang menggunakan sisa kayu terkumpul dari kawasan industri, komersial dan institusi sebagai bahan api telah dijalankan untuk menilai pelbagai impak operasi loji tersebut terhadap alam sekitar dengan menggunakan perisian SimaPro. Kaedah ReCiPe Midpoint (H) dipilih untuk menjalani pernilaian ini. Keputusan analisa kitaran hayat telah menunjukkan pelbagai kesan terhadap alam sekitar dalam penjanaan 1 kWh elektrik oleh loji janakuasa biojisim dan keputusan analisa tersebut turut diguna untuk membuat perbandingan dengan grid nasional dalam penjanaan elektrik sebanyak 1 kWh. Sejumlah 0.319 kg CO\textsubscript{2} eq gas rumah hijau dilepaskan ke atmosfera bagi setiap kWh elektrik yang dihasilkan oleh loji janakuasa biojisim tersebut berdasarkan faktor perubahan iklim dalam penilaian kitaran hayat. Kadar pelepasan karbon dioxide daripada penjanaan kuasa elektrik oleh loji ini adalah 96.1% lebih kurang berbanding dengan penjanaan kuasa elektrik oleh loji janakuasa konvensional di Malaysia iaitu sebanyak 0.82 kg CO\textsubscript{2} eq. Senario yang menunjukkan hubungan antara kadar pengurangan pelepasan karbon selaras dengan komitmen kerajaan Malaysia untuk mengurangkan intensiti pelepasan karbon sehingga 45% menjelang tahun 2030 telah dirangsang. Senario tersebut membuktikan penggunaan biojisim dan sisa pepejal dalam teknologi WtE adalah sangat bermanfaat bagi mencapai sasaran SEDA Malaysia dalam penjanaan kuasa boleh diperbaharui. Konklusinya, penggunaan teknologi WtE mampu melupuskan sisa pepejal, mengurangkan pelepasan gas rumah hijau ke atmosfera, serta pada masa yang sama meningkatkan komposi tenaga boleh diperbaharui dalam campuran penjanaan elektrik negara.
ACKNOWLEDGEMENTS

This dissertation would not have been possible without the help of many people in different ways. Foremost, I would like to express my sincere gratitude to my supervisors, Dr. Onn Chiu Chuen and Prof. Dr. Sumiani binti Yusoff for their continuous guidance and advice throughout the project.

Special acknowledgement dedicated to Mr. Aaron Lai from Theen Seng Paper Manufacturing Sdn. Bhd. for providing data for this project. I would also like to thank Dr. Ng Chee Guan and Mr. Jaron Keng for giving advice and technical help.

Special thanks to my colleagues and lecturers who has helped me in solving problems I faced throughout this project.

I wish to thank the Department of Civil Engineering, Faculty of Engineering, and University of Malaya (UM), Malaysia for their financial support to carry out this research project. The project was funded under the project BK020-2015 and project RF004A-2018.
# TABLE OF CONTENTS

Abstract ...................................................................................................................................................... iii
Abstrak ....................................................................................................................................................... iv
Acknowledgements ..................................................................................................................................... v
Table of Contents ..................................................................................................................................... vi
List of Figures ........................................................................................................................................... x
List of Tables ............................................................................................................................................ xii
List of Symbols and Abbreviations ...................................................................................................... xiii

## CHAPTER 1: INTRODUCTION ......................................................................................................................... 1

1.1 Background of Study .......................................................................................................................... 1
    1.1.1 Waste Management in Malaysia ............................................................................................ 1
    1.1.2 Waste-to Energy .................................................................................................................... 3
1.2 Problem Statement ............................................................................................................................. 5
1.3 Objectives of Study ............................................................................................................................ 9
1.4 Scope of Study .................................................................................................................................. 10

## CHAPTER 2: LITERATURE REVIEW ............................................................................................................ 11

2.1 Waste Management ............................................................................................................................ 11
    2.1.1 Waste Definition .................................................................................................................... 11
    2.1.2 Type of Solid Waste ............................................................................................................. 12
    2.1.3 Integrated Solid Waste Management .................................................................................... 14
    2.1.4 Concept of Waste Hierarchy ................................................................................................ 15
2.2 Overview of Global MSW Management .......................................................................................... 16
    2.2.1 Scenarios in Developed Countries ...................................................................................... 17
    2.2.2 Scenarios in Developing Countries ...................................................................................... 18
2.3 Solid Waste Management in Malaysia ................................................................. 20
  2.3.1 Background of Malaysia ............................................................................. 20
  2.3.2 Brief History of Malaysia MSW Management .............................................. 21
  2.3.3 Solid Waste Generation in Malaysia ............................................................. 25
  2.3.4 Scheduled Waste in Malaysia .................................................................... 26
  2.3.5 C&D Waste in Malaysia ............................................................................. 28
  2.3.6 Clinical Waste in Malaysia ........................................................................ 29
  2.3.7 MSW in Malaysia ....................................................................................... 30
    2.3.7.1 Composition ......................................................................................... 31
    2.3.7.2 Moisture Content ................................................................................ 32
    2.3.7.3 Calorific Value ..................................................................................... 33
  2.3.8 Waste Management Options in Malaysia ..................................................... 35
    2.3.8.1 Incineration ......................................................................................... 35
    2.3.8.2 Landfilling .......................................................................................... 36
  2.3.9 Challenges of Solid Waste Management in Malaysia .................................... 37
  2.4 Waste-to-Energy .............................................................................................. 39
    2.4.1 Waste-to-Energy Technology .................................................................. 39
    2.4.2 Waste-to-Energy Policies in Other Countries .......................................... 42
    2.4.3 Potential of Waste-to-Energy in Malaysia .............................................. 45
  2.5 Electricity Status in Malaysia .......................................................................... 47
    2.5.1 Electricity Generation ............................................................................... 47
    2.5.2 Energy Policies ......................................................................................... 48
    2.5.3 RE Policy .................................................................................................. 50
    2.5.4 Biomass as Potential RE .......................................................................... 52
  2.6 Greenhouse Gases Emission in Malaysia ......................................................... 53
    2.6.1 GHG from Waste ...................................................................................... 56
CHAPTER 3: METHODOLOGY ............................................................... 76

3.1 Case Study: Energy Recovery from Wood Waste ......................... 76
3.2 Data Collection .............................................................................. 78
3.3 LCA Methodology ........................................................................ 78
3.4 Goal and Scope Definition .............................................................. 80
3.5 Functional Unit .............................................................................. 80
3.6 System Boundary ........................................................................... 80
3.7 Limitation and Assumption ............................................................. 81
3.8 Impact Assessment Method ............................................................ 81

CHAPTER 4: RESULTS AND DISCUSSION ............................................. 84

4.1 Life Cycle Inventory ...................................................................... 84
4.1.1 General Process Flow ................................................................. 84
4.2 Inventories Selection ........................................................................ 86
4.3 Life Cycle Impact Assessment of Wood WtE Plant ....................... 90
  4.3.1 Impact Assessment by Processes of Wood WtE ..................... 93
  4.3.2 Sensitivity Analysis ................................................................. 96
4.4 Impact Assessment of Wood WtE Plant vs National Grid ............... 98
4.5 Potential of WtE to Reduce Impact from Landfill ......................... 100
4.6 Potential of WtE as Renewable Energy ......................................... 102

CHAPTER 5: CONCLUSION .................................................................. 105
5.1 Conclusion ....................................................................................... 105
5.2 Summary based on Objectives ......................................................... 106
  5.2.1 Environmental Profile of Wood WtE ..................................... 106
  5.2.3 Comparison of Wood WtE to National Grid in GHG Emissions .... 107
  5.2.1 Potential of Implementation of WtE in Malaysia .................... 108
5.3 Limitations ....................................................................................... 109
5.4 Recommendations ........................................................................... 110
References ............................................................................................ 111
List of Publications and Papers Presented .......................................... 121
LIST OF FIGURES

Chapter 1

Figure 1.1: Circular economy waste system ................................................................. 3

Chapter 2

Figure 2.1: Waste hierarchy ......................................................................................... 15

Figure 2.2: Composition of solid waste generation in Malaysia ............................... 25

Figure 2.3: Solid waste generation by states in Malaysia ........................................... 26

Figure 2.4: Scheduled waste generation in Malaysia .................................................. 27

Figure 2.5: C&D waste generation and projection ....................................................... 28

Figure 2.6: Quantity of clinical waste handled for destruction at incinerator ............... 29

Figure 2.7: Average MSW composition generated by Malaysian household .............. 31

Figure 2.8: Incinerators in Peninsular Malaysia ............................................................ 35

Figure 2.9: Typical WtE diagram ................................................................................ 39

Figure 2.10: Composition of electricity generation in Malaysia 2015 ...................... 47

Figure 2.11: Composition of power generation of commissioned RE installations 2016 ................................................................................................................. 51

Figure 2.12: Trend of greenhouse gases emission in Malaysia ............................... 54

Figure 2.13: Malaysia’s greenhouse gas emission by sector in year 2011 ................... 54

Figure 2.14: Sources of CO\textsubscript{2} emission in Malaysia .................................... 55

Figure 2.15: Sources of CH\textsubscript{4} emission in Malaysia ......................................... 56

Figure 2.16: Methane emission from landfills in Malaysia ...................................... 57

Figure 2.17: ISO 140040 Life cycle assessment framework .................................. 63

Figure 2.18: Life cycle assessment stages and boundaries ......................................... 65
Chapter 3

Figure 3.1: Photos taken during site visit.................................................................77
Figure 3.2: Material flows for biomass-fired power plant........................................78
Figure 3.3: System boundary of wood WtE...............................................................81
Figure 3.4: Categories and indicators at midpoint and endpoint
levels of ReCiPe method ..................................................................................83

Chapter 4

Figure 4.1: General process flow diagram..............................................................84
Figure 4.2: Network flow chart...............................................................................92
Figure 4.3: Graph of LCA characterization for different processes in wood WtE ....94
Figure 4.4: Comparison result between base scenario and scenario of power
generation using wood chips in Malaysia.........................................................97
LIST OF TABLES

Chapter 2

Table 2.1: Waste generation vs income level ................................................................. 16
Table 2.2: National Goal of MSW management in Malaysia ....................................... 24
Table 2.3: Typical moisture content of MSW .............................................................. 32
Table 2.4: Moisture content of Malaysian household MSW in % .............................. 32
Table 2.5: Net calorific values of waste ........................................................................ 34
Table 2.6: Calorific value of Malaysia MSW .............................................................. 34
Table 2.7: Number of landfills in Malaysia .............................................................. 36
Table 2.8: Cumulative RE Capacity Targets of Malaysia in MW ............................... 52
Table 2.9: Annual CO₂ avoidance in power generation with commissioned RE installation ................................................................. 58
Table 2.10: LCA tools with descriptions ..................................................................... 70
Table 2.11: Overview of common LCIA methodology ............................................... 72

Chapter 4

Table 4.1: Collected inventory data ............................................................................ 87
Table 4.2: Inventories for generation of 1kWh electricity fed into national grid by wood WtE plant ............................................................. 88
Table 4.3: Impact assessment of wood WtE in generating 1kWh of electricity ............... 90
Table 4.4: Impact assessment of wood WtE plant vs current national grid in generating 1kWh electricity ................................................................. 99
Table 4.5: Malaysia’s cumulative total RE target ....................................................... 102
Table 4.6: Potential of CO₂ avoidance as RE target is achieved ............................... 104
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDM</td>
<td>Clean Development Mechanism</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>DL</td>
<td>Distribution License</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Environment</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>FIAH</td>
<td>Feed-in Approval Holder</td>
</tr>
<tr>
<td>FU</td>
<td>Functional Unit</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>ICI</td>
<td>Industrial, Commercial and Institution</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>ISWM</td>
<td>Integrated Solid Waste Management</td>
</tr>
<tr>
<td>LA</td>
<td>Local Authority</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
</tr>
<tr>
<td>LCT</td>
<td>Life Cycle Thinking</td>
</tr>
<tr>
<td>LULUCF</td>
<td>Land Use, Land-use Change and Forestry</td>
</tr>
<tr>
<td>MEIH</td>
<td>Malaysia Energy Information Hub</td>
</tr>
<tr>
<td>MHLG</td>
<td>Ministry of Housing and Local Government</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
</tr>
<tr>
<td>NIMBY</td>
<td>Not In My Back Yard</td>
</tr>
<tr>
<td>NREBS</td>
<td>Natural Resources and Environment Board Sarawak</td>
</tr>
<tr>
<td>PPA</td>
<td>Power Purchase Agreement</td>
</tr>
<tr>
<td>RDF</td>
<td>Refuse Derived Fuel</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable Energy</td>
</tr>
<tr>
<td>SEDA</td>
<td>Sustainable Energy Development Authority</td>
</tr>
<tr>
<td>SIRIM</td>
<td>Standards and Industrial Research Institute of Malaysia</td>
</tr>
<tr>
<td>SWCorp</td>
<td>Solid Waste Management and Public Cleansing Corporation</td>
</tr>
<tr>
<td>SWOT</td>
<td>Strengths, Weaknesses, Opportunities, and Threats</td>
</tr>
<tr>
<td>WiE</td>
<td>Waste-to-Energy</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background of Study

1.1.1 Waste Management in Malaysia

Malaysia has endured significant increase in quantities, heterogeneity and complexity on the generated solid waste due to rapid growth in population, industrialization and urbanization. Local and regional authorities of Malaysia encounter controversial and serious issues in solid waste management. A proper waste management is crucial for: i) environmental and human health protection, ii) resources conservation such as energy, landfill space and materials, iii) aftercare-free waste management (Abas, 2014). Malaysia is facing challenge to design localized waste management strategies and policies which are economically viable, socially acceptable, as well as environmentally effective.

Malaysians generate solid waste of 0.5 - 2.5 kg per capita per day (Johari et al., 2014). In recent years, annual solid waste generation in Malaysia has surpassed 11 million tons and expected to reach 15.6 million tons by 2020. In fact, waste management standard of Malaysia is still not satisfied despite the problems include: i) incomplete and outdated documentation of generated waste such as generation rate, characteristic and composition of waste, ii) inefficient collection and storage systems iii) disposal of wastes with mixing of hazardous and toxic waste, iv) illegal dumping, and v) inefficient utilization of landfills space.

Disposal of solid waste to landfills is the most common waste management method in Malaysia. Although landflling is not the best option, it is nonetheless an
indispensable way of disposing waste cost effectively (Roy, 1997). Disposal of 95% of total MSW generated has resulted in more than 10 million tons of solid waste being disposed in landfills since Malaysia does not have integrated waste management system in large scale (Fauziah, 2013). Resource recovery has to be improved since waste disposal in Malaysia is mainly depends on the landfills. The recycling rate is very low with only 10.5% due to insufficient facilities for waste separation at source. The institutional as well as regulatory frameworks of Malaysia’s waste management are scattered and deficient.

There was significant change in the waste management policies since enforcement of National Solid Waste Management and Public Cleansing Act 2007 to transfer the waste management responsibilities to national level. Initially, the responsibilities were hold by local authorities. Human health protection and resources conservation had been stressed in National Strategic Plan for Solid Waste Management (NSWMP) (MHLG, 2005). Recently, the Sustainable Consumption and Production (SCP) concept had been introduced under 11th Malaysia Plan (2016-2020) for the government to take the lead in achieving an integrated development that covered economic growth, environmental protection and social inclusiveness. There is a national SCP blueprint that outlined areas and measures of priority to achieve green growth. The objective of this plan is transforming Malaysia to a resource and energy efficiency society with creation of green market, increment of RE share in energy mix, enhancement of side management demand, encouragement of low carbon mobility and holistic management of waste (EPU, 2015). In the national SCP blueprint, there are ten pathways to achieve the goals set by government in year 2030. The pathway that related to waste management in Malaysia is to create a circular economy waste system. All types of waste should be managed in a holistic manner based on a life cycle approach which extends beyond the entire disposal of the waste (SCP Malaysia, 2016).
Circular economy waste system that replaced linear model of taking – making – using – throwing is requiring fully adoption of reduce, reuse and recycle models for solid waste. The ultimate goal is to phase out conventional landfilling by year 2030 (SCP Malaysia, 2016).

1.1.2 Waste-to-Energy (WtE)

Waste-to-Energy (WtE) is a way of waste treatment where combustible waste is burnt in specialized engineered set up and converted to energy in the form of heat and electricity. WtE can solve the problems of waste management, GHG emissions and energy demand simultaneously (Pan et al., 2015).

Life-cycle thinking (LCT) is presented as a principle to guide resource management. Strategic goal to move towards a more sustainable consumption and production pattern has been set in order to decouple waste generation and resource utilization (Malek, 2012). Sustainability is the key criterion in waste management. Nowadays, people tend to choose more environment friendly way for waste disposal and gradually divert the waste from landfills.

WtE is a sustainable option for waste management as it is effective in reducing the weight and volume of waste, thus saving land space for landfilling. WtE has more
environmentally beneficial compared to landfilling because the aggressive greenhouse
gas, methane is not produced when waste is incinerated. WtE is able to convert the
waste into clean energy. The energy that produced is utilized for district heating in
countries with cold climate and also used for industrial processes in the form of steam.
Besides, electricity can be generated through WtE and sold to electricity grid. It is an
alternative source of energy that can help to curb increasing demand for electricity
generation since the global energy consumption is growing fast with the increase in
world population. Furthermore, electricity generated from WtE is more environmental-
friendly as electricity generated from combustion of fossil fuels has created various
environmental issues where the primary concerns will be emission of carbon dioxide
emissions. Energy from waste could be the solution for energy sustainability challenge
faced by electricity supply sector to maintain secure and reliable energy supply, also
ensuring the diversification of different energy resources (Ong et al., 2010).

Globally, there are more than 1200 WtE plants are operating across over 40
countries. WtE has been implemented successfully mostly in high-income countries.
For example, Sweden has achieved landfilling rate of 2% with installation of WtE plant
where the 32 WtE plants are supplying electricity for about 250,000 homes and also
providing heat for about 810,000 households. Sweden imports 700,000 tonnes solid
waste from neighbouring countries as fuel stock to generate electricity. WtE technology
is strongly developed in new countries along with the implementation of waste policy
and regulation such as in Thailand, China and South Korea (ISWA, 2013). Solid waste
incineration in a moving grate combustion system with combined heat and power
production is the most common WtE technology that has been used (Lausselet et al.,
2016).
1.2 Problem Statement

Malaysia has achieved consistent development in economic since its independence. The economic growth has brought along increment in population, rapid industrialization and urbanization. As a result, there has also been massive increase in the amount of solid waste generated in the country. Solid waste generated in Malaysia per capital has increased from 0.5 kg per capital daily in the 1980’s to 1 kg per capital daily in year 2008 and 1.17 kg per capita daily in year 2013 (National Solid Waste Management Department, 2013). Malaysians generate over 33,000 tonnes of solid waste per day, mostly from household which accumulated for 65%, 28% from commercial and institutional and 7% of industry waste.

Currently, solid waste management in Malaysia mostly depends on landfilling. About 95% of the national waste was land-filling without energy recovery (Agamuthu, 2017). Out of 294 landfills in Malaysia, only 163 are operational. Existing landfill sites are filling up rapidly despite constructing new landfill sites becomes very difficult due to high demands, increase of land prices and land scarcity especially in urban areas (Manaf et al., 2009). The main component of landfill gases (LFG), methane is a significant greenhouse gas while landfill leachate will cause pollution on groundwater and nearby surface water. The situation becomes worse as most landfills in Malaysia are non-sanitary landfills which lack of proper lining system and leachate treatment facilities. There are only 12% of sanitary landfills in the total existing disposal sites while the remaining are non-sanitary landfills or open-dump sites. A more efficient waste management system is needed urgently for Malaysia.

Waste management sector encounters problems that cannot be solved on its own. However energy sector is considered to be a perfect match because of its need to meet an increasing energy demand continuously (World Energy Council, 2016). Electrical
energy demand and consumption in Malaysia has risen extensively along with the growth of Malaysia’s GDP and population over the past few decades as energy is essential in driving Malaysia’s industrial and commercial developments, as well as ensuring desirable quality of Malaysians’ life by serving as a basic utility for social needs (Khor & Lalchand, 2014). It was reported that Malaysia is one of the largest electricity consumers among the member countries of Association of Southeast Asian Nations (Tang & Tan, 2013). There is an annual growth rate of 3.56% - 7.64% for electricity consumption from year 2005 till year 2012. Waste-to-Energy technologies emerged as sustainable ways to dispose the large quantities of solid waste and generate energy which can be contributed to energy production mix. A good waste disposal strategy and green energy production can be achieved simultaneously as the WtE technologies are implemented following sustainability principles (World Energy Council, 2016).

Malaysia is still on track to reduce GHGs emission significantly in mitigating climate change. The Malaysian greenhouse gas inventory covers three major GHGs. Carbon dioxide contributed the largest share which was 72% in Malaysia’s GHGs emission, followed by methane accounted for 23% and 5% of nitrous oxide. From year 1990 to 2010, electricity and heat production contributed to the majority of the carbon dioxide emissions. This is due to diesel-powered generators and coal-powered generators are widely used in Malaysia to generate electricity. The highest emission of methane came from landfill and dumpsites which made up about 46% (Ministry of Natural Resources and Environment Malaysia, 2011). This is because decomposition of organic waste at landfills under anaerobic conditions will generate huge amount of LFG that contains 50–60% methane and 30–40% carbon dioxide by volume. WtE technologies can definitely help in CO₂ and CH₄ emissions reduction since implementation of WtE technologies will lessen the quantity of solid waste being
disposed at landfills. Waste becomes a source of RE for optimization of fuel mix to reduce Malaysia’s dependency on fossil fuels in electricity generation. Hence, GHG emissions reduction will be achieved as a portion of fossil fuels are substituted by wastes for energy production.

It is crucial to take account of the amount, composition and characteristics of different types of solid waste when considering waste as energy resource. Since awareness of Malaysians towards waste separation at source is still very low, the composition of solid waste generated especially from household is usually complicated and all the waste is mixed. The major fractions of solid waste in Malaysia include food waste, plastic, paper, diapers, textiles and garden waste. The largest composition of solid waste generated by Malaysian household is food waste constituting 44.5%. Therefore, the MSW with high moisture content and organic constituents may be not suitable for incineration, where energy conversion of bio-chemical methods will be more preferable. WtE incineration should only be considered for the waste with an average net calorific value of 7 MJ/kg and above (World Energy Council, 2016). The lower heating value of MSW in Malaysia is only 6.325 MJ/kg. Wood waste with calorific value more than 7 MJ/kg is more suitable for WtE incineration. WtE plants indeed have great potential to be installed in Malaysia but proper planning is needed to locate them strategically for meeting the demand and logistics as quantity of waste generation in Malaysia is varied for different states and regions though the supply of combustible solid waste is stable. Central region (KL and Selangor) has the highest amount of solid waste generated which was about 9,702 tonnes per day. Eastern region generated less amount of solid waste, approximately 3,862 tonnes per day (National Solid Waste Management Department, 2013).
Life cycle assessment (LCA) is a useful tool in assessing multiple environmental impacts of providing products and services. Many countries especially the developed ones are now focusing on the sustainable solid waste management perspective. Previous studies regarding LCA on solid waste management options had been conducted at different countries all over the world such as Austria, Brazil, China, Denmark, Singapore, Switzerland, Thailand, and Turkey. However, there are very few LCA researches have been conducted on waste management sector in Malaysia. LCA of MSW management was done on landfilling by Saheri et al. (2012). In this study, LCA is used to weigh up three scenarios with different composition of discarded MSW into open dump and sanitary landfill by using SimaPro software. Results had shown all scenarios are having high amount of different potential impacts but the third scenario (100% sanitary landfill) is preferable than the others (Saheri et al., 2012). Besides dump site and sanitary landfill, other available solid waste management options such as anaerobic digestion, composting, incineration and waste-to-energy should be identified. LCA methodology can be applied widely on this field to assess, analyze and compare the impacts of MSW management options so that sustainable solid waste management system can be formed in Malaysia.
1.3 Objectives of Study

The objectives of this research are:

1) To create environmental profile for selected Waste-to-Energy technology using life cycle assessment methodology.

2) To compare the impacts of electricity generation between the biomass-fired power plant and current national grid.

3) To determine the potential of implementation of wood Waste-to-Energy in Malaysia based on the impact assessment modelling result.
1.4 Scope of Study

This study focuses on a case study in Malaysia to evaluate the potential of waste-to-energy in developing countries from the perspective of life cycle assessment. The objective of study is to develop life cycle inventory (LCI) for a wood WtE plant in Selangor and create its environmental profile. The scope of the study is limited on operation of the wood WtE plant. The environmental profile is set up through data contribution from the company that owned the plant and partially referred to database provided in LCA software and also related journals. Modelling was carried out with chosen LCA software which is SimaPro based on Life Cycle Impact Assessment (LCIA) methodology.
CHAPTER 2

LITERATURE REVIEW

2.1 Waste Management

2.1.1 Waste Definition

Waste is defined as (i) ‘any discarded, rejected, abandoned, unwanted or surplus matter, whether or not intended for sale or for recycling, reprocessing, recovery or purification by a separate operation from that which produced the matter’; or (ii) ‘anything declared by regulation (after consultation under section 5A) or by an environment protection policy to be waste, whether of value or not’ according to Australia EPA Waste Guideline (2009).

In Malaysia, solid waste and solid waste management was not specifically defined in the past for a few decades (Zamali et al., 2012). In year 1971, Solid Waste and Public Cleaning Management Act was amended and revised in year 2007. According to this act, ‘solid waste’ is defined as i) ‘any scrap material or other unwanted surplus substance or rejected products arising from the application of any process’, ii) ‘any substance required to be disposed of as being broken, worn out, contaminated or otherwise spoiled’; or iii) ‘any other material that according to this act or any other written law, is required by the authority to be disposed of but does not include scheduled wastes as prescribed under the Environmental Quality Act 1974 (Act 127), sewage as defined in the Water Services Industry Act 2006 (Act 655) or radioactive waste as defined in the Atomic Energy Licensing Act 1984 (Act 304)’.

Controlled solid waste is defined as ‘any solid waste falling within any of the following categories: i) commercial solid waste, ii) construction solid waste, iii) household solid waste...
waste, iv) industrial solid waste, v) institutional solid waste, vi) imported solid waste, vii) public solid waste, and viii) solid waste which may be prescribed from time to time’.

2.1.2 Type of Solid Waste

a) Municipal solid waste - MSW is defined as i) ‘trash or garbage that consists of everyday items such as product packaging, grass clipping, furniture, clothing, bottles, food scraps, newspaper, appliances and batteries’; ii) ‘not included are materials that may also be disposed in landfills but are not generally considered MSW such as construction and demolition debris, municipal wastewater treatment sludge and non-hazardous industrial wastes’ by Environmental Protection Agency (EPA). MSW which is also called urban solid waste is the type of waste that includes i) household wastes – ‘any solid waste generated by a household, and of a kind that is ordinarily generated or produced by any premises when occupied as a dwelling house, and includes garden waste’; and ii) commercial wastes or institutional solid waste – ‘any solid waste generated by a) any premises approved under any written law or by the State Authority for use wholly or mainly for religious worship or for charitable purposes; b) any premises occupied by any Federal or State Government department, any local authority or any statutory body; c) any educational premises; d) any healthcare facilities including hospitals, clinics and health centres or e) any premises used as public zoos, public museums, public libraries and orphanages’. Generally, there are five categories of MSW which are: i) biodegradable waste: food and kitchen waste, ii) recyclable material: paper, glass, bottles, cans, metals and certain plastics, iii) inert waste: construction and demolition waste, dirt, rocks and debris, iv) composite wastes: discarded clothing and plastics, v) domestic hazardous waste which is also known as household hazardous waste: medication, electronic waste, paints, chemicals, light bulbs, fluorescent tubes, spray cans, batteries, fertilizer and pesticide containers.
b) Industrial waste - ‘solid waste generated from any industrial activity (Solid Waste and Public Cleansing Management Act 672, 2007)’ including rubbish, ashes, demolition and construction wastes. Some of the waste could also include hazardous and special waste.

b) Hazardous waste – ‘Any waste falling within the categories of waste listed in the First Schedule of the Environment Quality (Scheduled Wastes) Regulations 2005’. Hazardous waste contains substances posing substantial danger or hazards to human, plant, or animals as well as the environment. The waste exhibits following characteristic:
   i) ignitability, ii) corrosive, iii) reactivity, or iv) toxicity.

c) E-waste - Under the EQA 1974 (Act 127), e-waste is defined as ‘waste from electrical and electronic assemblies containing components such as accumulators, mercury-switches, glass from cathode-ray tubes and other activated glass or polychlorinated bi-phenyl capacitors, or contaminated with cadmium, mercury, lead, nickel, chromium, copper, lithium, silver, manganese or polychlorinated biphenyl’.

d) Clinical waste – ‘Any waste consisting wholly or partly of human or animal tissue, blood or other body fluids, excretions, drugs or other pharmaceutical products, swabs or dressings, or syringes, needles or other sharp instruments, being waste which unless rendered safe may prove hazardous to any person coming into contact with it; and any waste arising from medical, nursing, dental, veterinary, pharmaceutical or similar practices, investigation, treatment, care, teaching or research, or the collection of blood for transfusion, being waste which may cause infection to any person coming into contact with it’. In Malaysia, clinical waste is classified as scheduled waste under the Environmental Quality (Scheduled Wastes) Regulations, 2005 which includes: i) SW403 – Discarded drugs containing psychotropic substances or containing substances that are toxic, harmful, carcinogenic, mutagenic or tetrogenic; ii) SW404 – Pathogenic
and clinical wastes and quarantined materials; iii) SW421 – A mixture of scheduled wastes; and iv) SW424 – A mixture of scheduled and non-scheduled wastes.

2.1.3 Integrated Solid Waste Management (ISWM)

ISWM is referred to integrating several management programs and technologies to strike waste management objectives and targets. It is a complete waste management which covering prevention, treatment, recycling, recovery, treatment and disposal programs (Chandrappa & Das, 2012). The preference of technologies or programs can be ranked based on the problems at the targeted areas by evaluating the data of solid waste generation as well as impacts to environmental from cradle to grave of the selected waste management technology. Waste management planning should consider economic, environmental, financial, institutional, legal, social, and technical factors (Chandrappa & Das, 2012).

An ISWM plan should include following components: i) waste management related aims, objectives, initiatives and policies, ii) city scale and character, population distribution, climate and development, iii) all data on waste such as composition and characteristic, iv) identification of options, v) determination of the most suitable environmental option, vi) specification of the scale, quantity, transportation, distribution of collection, disposal and treatment systems in proposed plan, vii) requirements on the proposed monitoring and controls, viii) associated regulatory arrangements and institutional reforms, ix) financial assessment of the plan, x) finance and revenues sources related to the development and operation of the plan, xi) requirements for management, xii) period of implementation plan at least 5 to 10 years, with immediate action plan for the first 2 to 3 years, xiii) outline of public consultations, xiv) outline of the detailed program for waste management facilities, and xv) assessment of GHG emissions (World Bank, 2012).
In short, to plan an ISWM, the needs must be first identified where types, quantities and characteristics of the waste to be managed should be clarified. Then, existing policies, regulations and legislations regarding waste management in the country should be reviewed. Next, objectives of project can be established and available options or components should be list out. ISWM system will be formed and implemented after choosing the most suitable components. The ISWM system should be evaluated after implementation. ISWM planning should consider and include: i) Cost Benefit Analysis (CBA), ii) Material Flow Analysis (MFA), iii) Life Cycle Assessment (LCA), iv) Risk Assessment (RA), v) Environmental Impact Assessment (EIA), vi) Strategic Environmental Assessment (SEA), vii) Socioeconomic Assessment (SoEA), viii) Sustainable Assessment (SA), and ix) recent waste generation trends (Chandrappa & Das, 2012).

2.1.4 Concept of Waste Hierarchy

The “waste hierarchy” ranks the options for waste management based on the best way to treat the waste for the sake of environment. The waste hierarchy was introduced since 1970s as public started to consider the waste management practice issues. The waste hierarchy has been used by governments, industries, environment organizations and educators as a guide for creating waste policy and programs.

Figure 2.1: Waste hierarchy (Abas, 2014)
The hierarchy is outlined as follows: i) minimize waste generation, ii) reuse the waste, iii) recycle the waste, iv) energy recovery for non-recyclable waste, and v) final disposal in landfills. In fact, waste management has impacts in terms of environment, social and economic. Thus, any interpretation of the waste hierarchy should take these impacts into account.

The hierarchy showed preferred options priorities based on sustainability concept. Sustainability in waste management can be referred as waste recovery to extract valuable materials with the least consumption of space and energy, as well as reduce environmental loading. The general objectives for a sustainable waste management are: i) human health and environmental protection, ii) resources conservation, and iii) aftercare-free waste management (Abas, 2014).

2.2 Overview of Global MSW Management

Composition and quantity of solid waste is varied for different regions. The characteristics and quantity of MSW reflects living standard, as well as life style of the region. Table 2.1 shows the waste generation per capita by countries’ income level.

Table 2.1: Waste generation vs income level (World Bank, 2012)

<table>
<thead>
<tr>
<th>Income Level</th>
<th>Waste Generation Per Capita (kg/capita/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Boundary</td>
</tr>
<tr>
<td>High</td>
<td>0.70</td>
</tr>
<tr>
<td>Upper Middle</td>
<td>0.11</td>
</tr>
<tr>
<td>Lower Middle</td>
<td>0.16</td>
</tr>
<tr>
<td>Lower</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 2.1 showed that low income countries have low waste generation rate which is about 0.6 kg/capita/day. Countries with low income commonly lack of effective waste management. Average rate of waste generation for countries with lower middle income
is 0.79 kg/capita/day while the rate for countries with higher middle income is slightly higher, approximate 1.2 kg/capita/day. High income countries generated high volume of waste per capita which was about 2.1 kg/capita/day. However, the volume of MSW stream was low in most developed countries as they emphasized on waste separation and recycling to reduce amount of waste that reached final disposal stage.

2.2.1 Scenarios in Developed Countries

In developed countries, the rate of waste generation is much higher than developing and under-developed countries. Solid waste in developed countries usually contains higher fraction of non-biodegradable and the quantity is always larger than solid waste in developing and under-developed countries. Such trends are because of excessive consumption on packaging material, lack of scrap picking and dealers (Chandrappa & Das, 2012). This is because citizens in developed countries generally have high-paid jobs so they consume more, thus generate more waste. Not much people will do scrap picking since most of the people in developed countries have high income jobs. Composition of generated solid waste can be differed due to culture and habit

An effective waste management system is usually well established in developed countries with source reduction, collection, recycling, energy recovery and landfilling measures. Source reduction is being more successful in developed countries because people there are having awareness towards environmental protection. Developed countries emphasize public education on 3Rs concept as well as separation of waste at source. The rate of recycling for developed countries is invariably higher than other countries. The manufacturers are focusing in designing eco-friendly products. Collection of recyclable material is commonly regulated. The sorting processes usually happen in transfer stations by using advanced facilities. Incineration is a very common waste disposal method in developed countries especially at areas with low availability
of land and high land cost. Most incinerators would have pollution control equipment and energy recovery system which either produce heat or generate electricity. Standards and regulations are usually implemented to monitor the emissions from incinerators.

Most landfills in developed countries are sanitary landfills with equipped with liners, leachate collection and treatment systems, as well as gas collection and leakage detection system. Currently, developed countries tend to divert the waste from landfills and emphasize on post closure use of the landfill sites.

There are various waste management policies that have been implemented. In some advanced cities, the waste collection fee will be charged according to volume of waste disposed. For example, South Korea has successfully reduced 30% of total waste generated by implementing regulations for recyclable wastes separation and also charge collection fee based on volume of waste disposed since year 1995 (World Bank, 1999). Cities in Japan are actively promoting various waste reduction strategies. As an example, ‘Osaka Recycling Monthly’ is held to encourage residents in neighborhood to exchange unused items such as electrical appliances or furniture.

2.2.2 Scenarios in Developing Countries

Generally, municipal solid wastes in developing countries are commonly high in moisture contain and organic waste composition, but relatively low in calorific value. Paper and plastic waste are generated at an almost equal percentage in waste composition. Developing countries are the largest contributor of global plastic wastes due to durability and broad range of plastic usage, low cost of plastic production, as well as lacked of policy and regulations related to plastic utilization. Developing countries also generate large amount of industrial waste because waste minimization technology is not adopted and given attention.
Source reduction is not given much attention in developing countries. Public awareness towards 3R concept is not enough though parts of people have started to concern environmental issues. Informal recycling of materials has been dominant in developing countries. Recyclables such as metal, aluminium, paper, plastics and electronic waste will be picked out from mixture of MSW by the rag pickers (Kaseva and Gupta, 1996). Most recyclable materials are collected by rag pickers before selling to larger dealers and wholesalers. The common practice to handle the recyclable materials in developing countries is either to process locally or be exported (Vesilind, 2002). Number of transfer stations is less and only available in certain areas. Sorting and processing technology is not advanced. For waste disposal, the most common method will be disposed to landfills which are usually sanitary landfills. Open dumpsites are being closed gradually. Although some incinerators are being used, the incinerators may face operational and financial problems. Besides, emissions-related regulations in developing countries are not too strict, thus the air pollution control equipment for incinerators are not effective as installed in developed countries. Clean Development Mechanism (CDM) projects for landfill gas are very common in developing countries.
2.3 Solid Waste Management in Malaysia

2.3.1 Background of Malaysia

Malaysia is a tropical country located in Southeast Asia. Malaysia is composed of 11 states in the Peninsular Malaysia and 2 states in the island of Borneo with total land area of 330,803 km$^2$. The capital city of Malaysia is Kuala Lumpur.

Malaysia is hot and humid throughout the year. The average temperature for Malaysia is 27°C. Malaysia has high relative humidity ranging between 80-90% with average rainfall of 2750mm per year.

Malaysia is a multi-ethnic country which consists of four major ethnic groups which are Malays (50.1%), Chinese (22.6%), Indigenous (11.8%), Indian (6.7%) and other minor ethnic groups (8.8%). Malaysia’s total population is estimated at 31.7 million at year 2016 with 1.5% of annual growth rate. The gender ratio in Malaysia is quite equally distributed where ratio of males to females is 107 to 100. Among the 31.7 million persons, 10.3% of them are non-Malaysian citizens (Department of Statistic Malaysia, 2016).

Currently, Malaysia is an upper middle income country with GDP of 296.28 billion US dollar in year 2015. Malaysia has successfully transformed into an emerging diversified economy from the stage of economic domination by raw materials and natural resources production during 1970’s and became one of the main exporters of palm oil, natural gas, as well as electrical and electronic components globally.
2.3.2 Brief History of Malaysia MSW Management

Before 1970s, solid waste management was handled by the district public health departments in respective districts. Government had no policy in MSW management. During 1970s, the local authorities took the responsibilities on solid waste management and public cleansing through the provisions of Local Government Act 1976 (Act 171) and Street, Drainage and Building Act 1976 (Act 133) (Fauziah and Agamuthu, 2012). MSW collection services mainly catered the public places such as wet-markets while housing schemes in the urban areas were having irregular collection when the service was first introduced. The service mainly involved solid waste hauling from the collection areas to designated dumping sites. In late 1970s, there was further improvement in the waste management system to prevent proliferation of disease and degradation of environmental quality due to population growth (The Star, 2007). State governments played a role to monitor local authorities’ activities. Responsibility of federal government was to give technical and financial support to local authorities for improving the solid waste management system. In order to raise the awareness of Malaysians on solid waste management and environmental protection, a policy called ‘Action Plan for a Beautiful and Clean Malaysia (ABC)’ emerged in 1988. However, this plan was not implemented or authorised completely. In year 1993, Ministry of Housing and Local Government initiated a recycling program but it failed due to less commitment and lack of awareness among Malaysians.

During September 1995, government decided to federalise and privatise SWM services. Federal Government took over the responsibility. Besides, participation and investment of private sector in SWM was considered as a way to provide more cost effective and efficient services. Since 1 January 1997, the responsibility of 48 local authorities in SWM has been privatized to 2 concession companies which were i) Alam
Flora Sdn Bhd for Central Region, and ii) Southern Waste Sdn Bhd for the Southern Region. For Northern Region, it was under interim regime for a year before full privatisation was implemented. Local authorities of Kelantan, Terengganu, Sabah and Sarawak states continued to hold the responsibility for solid waste management (Yahaya and Larsen, 2008).

In year 2007, Solid Waste and Public Cleansing Management Corporation Act 2007 (Act 672) was passed by Parliament on 17 July 2007 and gazetted on 30th August 2007. Act 672 empowered Federal Government to fully handle the management of solid waste and public cleansing. This act was implemented in September, 2011. In conjunction with the implementation of Act 672, two bodies were established which are:

i) Department of National Solid Wastes Management (JPSPN)

JPSPN was established under Ministry of Urban Wellbeing, Housing and Local Government on 1st July 2007 with implementation of Act 672. Generally, the department’s main function was to create policies, plans and strategies relating SWM. It also responsible for setting SWM related standards, specifications, guidelines and code of practices. It had the right to give approval and license. Besides, it formulated plan for SWM facilities from the aspects of type, size, location, scheme, term and condition for the facilities.

ii) Solid Waste Management and Public Cleansing Corporation (SWCorp)

Besides Act 672, Parliament in 2007 also passed the Solid Waste and Public Cleansing Management Corporation Act 2007 (Act 673). SWCorp was established on 1st June 2008 to undertake the SWM related tasks in a professional and competent manner. The corporation had the right to control and solve solid waste management and public cleansing related matters. Solid waste management related issues at all levels including
Federal, State was under its responsibilities. It acted as a regulatory body to ensure compliance with the standards, specifications, guidelines and code of practices set by JPSPN and it was also empowered to enforce Act 672. Besides, it outlined and proposed policies, plans and strategies relating solid waste management and public cleansing. It also responsible for identifying and evaluating MSW management facilities such as sanitary landfill, transfer station, incineration technology, recycling technology and treatment plant before proposing to government. The corporation was also making an effort to promote public participation and raise public awareness in addition to improve public cleansing and solid waste management services’ quality for Malaysians.

In year 2011, Federal Government decided to extend the privatisation scheme for 22 more years of concessionaire agreement after 14 years of interim concessionaire since year 1997. Contracts were awarded based on regions to 3 concessionaire companies which were: i) Alam Flora Sdn Bhd - Federal Territory of Kuala Lumpur, Putrajaya, Pahang, Terengganu and Kelantan (Central and East zones), ii) SWM Environment Sdn Bhd: Johor, Melaka and Negeri Sembilan (Southern zone), and iii) Environment Idaman Sdn Bhd - Kedah and Perlis (Northern zone).

Since 1st September 2012, a ‘2+1 collection system’ had been implemented in the eight states under the National Solid Waste Management Department with waste collection being carried out once every two days for residual wastes and once every week for recyclable wastes, bulky wastes and green wastes. Besides, new standards on waste bins and garbage collection trucks were being implemented. There was also the enforcement of Key Performance Index (KPI) on garbage collection schedule (Agamuthu, 2017). Table 1.2 showed the waste management goals of Malaysia.
Table 2.2: Waste management goals in Malaysia (Samsudin and Don, 2013)

<table>
<thead>
<tr>
<th>Treatment Methods</th>
<th>Percentage (%)</th>
<th>2002</th>
<th>2006</th>
<th>Target 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling</td>
<td></td>
<td>5.0</td>
<td>5.5</td>
<td>22.0</td>
</tr>
<tr>
<td>Composting</td>
<td></td>
<td>0.0</td>
<td>1.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Incineration</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>16.8</td>
</tr>
<tr>
<td>Inert landfill</td>
<td></td>
<td>0.0</td>
<td>3.2</td>
<td>9.1</td>
</tr>
<tr>
<td>Sanitary landfill</td>
<td></td>
<td>5.0</td>
<td>30.9</td>
<td>44.1</td>
</tr>
<tr>
<td>Other disposal sites</td>
<td></td>
<td>90.0</td>
<td>59.4</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>100.0</strong></td>
<td><strong>100.0</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

At year 2002, almost 95% of the national waste entered the landfills with only recycling rate of 5%. The recycling rate increased up to 10.5% in year 2012 and 15% in year 2014. The government had also launched various campaigns and programs with in order to educate public and create awareness on 3Rs. Previous 3Rs campaigns launched by the government in 1990’s and year 2000 failed to change public’s attitudes and habits over the years. Additionally, Malaysia started to enforce waste separation on 1st June 2016 but not all states implemented it. Malaysia government had targeted to achieve 22% of material recycling rate by 2020. Other than recycling, government was also planning for food waste management. Almost 50% of solid waste being disposed to landfills was food waste. For instance, the Kuala Lumpur City Council (DBKL) had initiated campaigns to clean and beautify the Malaysian capital by converting food waste and organic waste into fertilizers through the Local Agenda 21 Kuala Lumpur (LA21KL) program (Agamuthu, 2017).
2.3.3 Solid Waste Generation in Malaysia

Malaysia generated about 33,000 tonnes of solid waste per day, with an average of 1.17 kg per capita per day (National Solid Waste Management Department, 2013). Figure 2.2 showed composition of solid waste generation in Malaysia.

![Figure 2.2: Composition of solid waste generation in Malaysia (PEMANDU, 2015)](image)

Most of the solid waste in Malaysia was generated from household which accumulated for 65%. 28% of generated solid waste came from commercial buildings and institutions such as shopping malls, central bus stations, hotels, hospitals, offices, schools, mosques and police stations. 7% of solid waste was industry waste including: a) basic metal and fabricated metal, b) electrical & electronic products, c) food and beverage, d) textile and apparel, e) plaiting materials and straw manufacturing, f) paper and paper product, g) chemical, petrochemical and plastic products, h) motor vehicles and transport equipment, i) wood, cork and wood products, j) machinery, and k) non-metallic mineral product.

Figure 2.3 presented solid waste generated by states in Malaysia. Amount of solid waste generated was different for each state in Malaysia.
The largest amount of solid waste in Malaysia was generated by Central region (Federal Territory of Kuala Lumpur and Selangor) as these areas had the highest population in whole of Malaysia. With high economic development and extent of urbanization, KL and Selangor generated the highest percentage of total solid waste generated which was 25%, about 9,702 tonnes per day. Johor state generated 12% of total solid waste which ranked second in the whole of Malaysia. Eastern region such as Kelantan and Terengganu states generated smaller amount of solid waste, which was lower than 5% of the total amount of solid waste generated respectively. East Malaysia (Sabah, Sarawak and Federal Territory of Labuan) contributed 20.32% of the total amount solid waste generated.

2.3.4 Scheduled Waste in Malaysia

In Malaysia, hazardous waste is known as scheduled waste which referred to any waste falling within the 107 categories of hazardous waste listed in the First Schedule of
the EQA 1974 according to Environmental Quality (Scheduled Wastes) Regulations 2005. Figure 2.4 showed amount of hazardous waste generated in Malaysia from year 2000 to 2012.

![Figure 2.4: Scheduled waste generation in Malaysia (Agamuthu, 2017)](image)

Scheduled waste generation in Malaysia kept increasing from year 2000 to 2010. There was a drastic increase in the amount of hazardous waste generation from year 2005 to 2006. From 2000 to 2010, the amount of scheduled waste had increased for 446% in 10 years. Due to accelerating pace of industrialization, Malaysia encountered numerous assaults on the environment.

The management of scheduled waste in Malaysia was considered well compared to other types of waste. In year 2012, there was 446 off-site recovery facilities had been licensed for with 153 for e-waste, 58 for oil/mineral sludge / spent coolant, 37 for heavy metal sludge / rubber, 34 for used container / contaminated waste/ink/paint/lacquer, 31 for solvent and 27 for acid/alkaline respectively. About 4% of scheduled waste generated was handled by Kualiti Alam Sdn. Bhd. who owned and operated the only integrated hazardous waste management centre in Malaysia (Agamuthu, 2017).
2.3.5 C&D Waste in Malaysia

Rapid growth in construction industry has significantly contributed to increasing of construction and demolition waste generation in the form of concrete, building debris and mixture of residual materials from the clearance of sites. Figure 2.5 presented the amount of C&D waste generation in Malaysia and its projection at year 2020.

![Figure 2.5: C&D waste generation and projection (PEMANDU, 2015)](image)

The total C&D waste generation in year 2007 was 9.7 million tonnes, 10.4 million tonnes in year 2010 and 11.8 million tonnes in year 2015. About 85% of the C&D waste was generated at Peninsular Malaysia while KL city and Selangor state contributed half of the Peninsular Malaysia’s C&D waste due to their advanced state of development. The compound annual growth rate for C&D waste generation is 2.5%. C&D waste generation projected to reach 13.3 million tonnes per year by 2020.

Generally, C&D waste is not suitable for incineration. 60% of the waste was expected to be dumped to private land or possibly illegal dumped. Only 15% of the waste was sent to inert landfill for disposal while 20% was buried or burnt on site. There was 5% of C&D waste being recycled.
2.3.6 Clinical Waste in Malaysia

Proper clinical waste management is crucial to avoid risks to human health and the environment due to the heterogeneity within the waste stream. 10% to 25% of the clinical waste is considered hazardous while 75% to 90% of waste is considered as general waste (non-hazardous waste). Hazardous clinical waste can be very dangerous as exposure can result in disease or injury since it may be genotoxic, hold infectious disease or contained hazardous chemicals / pharmaceutical residues / radioactive compound. Such waste is suitable to be incinerated. Figure 2.6 showed the amount of clinical waste handled for destruction at incinerator from year 2009 to 2013.

![Figure 2.6: Quantity of clinical waste handled for destruction at incinerator (Agamuthu, 2017)](image)

The generation of clinical waste in Malaysia increases from year to year. The amount of clinical waste being incinerated in year 2013 has increased by 17.5% as compared to 2009. This is due to the growth and improvement of healthcare services. Quantity of healthcare institutions in Malaysia is gaining at rapid rate, so as the clinical waste generated.
2.3.7 MSW in Malaysia

The major component solid waste generated in Malaysia is municipal solid waste (MSW). There has been massive increase in the amount of MSW generated along with economic and population growth, rapid industrialization and urbanization in Malaysia. The quantity of MSW generation in Malaysia has increased from 19,000 ton/day in year 2005 to 33,000 ton/day in year 2013. In recent years, generation of MSW in Malaysia has exceeded 11 million tons yearly and is expected to reach 15.6 million tons by year 2020. Globally, the average rate of increase in MSW generation is 3% according to World Bank (2012) but annual generation of MSW in Malaysia has increased 6.7% these years. Rate of increment in MSW generation of our country is twice higher than the normal rate.

One of the general rules for WtE incineration is the amount of incoming waste. WtE incineration can only be considered for the amount of solid waste generated with minimum of 100,000 tonnes/year including seasonal changes such as during holidays and festivals based on ISWA (2013). Malaysia definitely fulfilled this requirement as supply of combustible solid waste is stable throughout the year and huge amount of solid waste is generated daily.
2.3.7.1 Composition

Most of the MSW generated in developing counties are decomposable and recyclable. It was reported that waste is dominated by organic material in all the Asian countries except Japan (Agamuthu & Fauziah, 2007). Figure 2.7 presented the average MSW composition generated by Malaysian household.

![Figure 2.7: Average MSW composition generated by Malaysian household (National Solid Waste Management Department, 2013)](image)

According to the survey done by National Solid Waste Management Department (2013), MSW in Malaysia was dominated by organic wastes. The type of MSW generated mostly by Malaysian household was food waste constituting 44.5%. Malaysians generated about 15,000 tonnes of food waste per day. Plastics and paper waste made up 13.2% and 8.5% respectively of the total MSW. Disposable diapers and feminine sanitary products made up approximately 12.1% of the total MSW generated per day. This is mainly because of user-friendly and easily accessible of the products in market. Besides, garden waste and wood were 5.8% and 1.4% respectively. Composition percentage of the total MSW generated for glass, metal and textile were 3.3%, 2.7% and 3.1% respectively.
2.3.7.2 Moisture content

Moisture content is ratio of mass of water in the waste to the mass of solid in the waste. Waste with high moisture content is not suitable for WtE incineration. Supplemental fuel is needed to be added during incineration for waste with high moisture content. Table 2.3 showed moisture content of different types of MSW.

<table>
<thead>
<tr>
<th>Component</th>
<th>Range (%)</th>
<th>Typical (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food waste</td>
<td>50-80</td>
<td>70</td>
</tr>
<tr>
<td>Paper</td>
<td>4-10</td>
<td>6</td>
</tr>
<tr>
<td>Cardboard</td>
<td>4-8</td>
<td>5</td>
</tr>
<tr>
<td>Plastics</td>
<td>1-4</td>
<td>2</td>
</tr>
<tr>
<td>Textiles</td>
<td>6-15</td>
<td>10</td>
</tr>
<tr>
<td>Rubber</td>
<td>1-4</td>
<td>2</td>
</tr>
<tr>
<td>Garden trimming</td>
<td>30-80</td>
<td>60</td>
</tr>
<tr>
<td>Wood</td>
<td>15-40</td>
<td>20</td>
</tr>
<tr>
<td>Tin cans</td>
<td>2-4</td>
<td>3</td>
</tr>
<tr>
<td>Leather</td>
<td>8-12</td>
<td>10</td>
</tr>
<tr>
<td>Glass</td>
<td>1-4</td>
<td>2</td>
</tr>
<tr>
<td>Non-ferrous metals</td>
<td>2-4</td>
<td>2</td>
</tr>
<tr>
<td>Dirt, ashes, bricks</td>
<td>6-12</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2.4: Moisture content of Malaysian household MSW in % (National Solid Waste Management Department, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Urban Household</th>
<th>Rural Household</th>
<th>Malaysian Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Cost</td>
<td>Medium Cost</td>
<td>High Cost</td>
</tr>
<tr>
<td>As Generated</td>
<td>53.84</td>
<td>52.30</td>
<td>51.96</td>
</tr>
<tr>
<td>As Discarded</td>
<td>56.53</td>
<td>59.13</td>
<td>58.87</td>
</tr>
<tr>
<td>As Disposed</td>
<td>59.65</td>
<td>60.55</td>
<td>59.45</td>
</tr>
</tbody>
</table>

Table 2.4 shows the moisture content of MSW generated by Malaysian household in %. Moisture content of MSW in Malaysia is relatively high which reached about 59.5% as MSW is disposed in landfills. The moisture content of MSW as disposed will be higher than during generated and discarded. The moisture content of
the waste gets higher as moving from generation point to disposal site due to increment of food content and reduction in recyclable material. In addition, precipitation can be a factor to influence the moisture content. The moisture content of waste will become higher during raining season. On the other hand, MSW generated by rural household has moisture content (42% - 47%) slightly lower than MSW generated by urban household (52% - 54%).

2.3.7.3 Calorific Value

Energy value of waste components is dependent on its calorific value (CV). To find out CV of the waste components, heating value should be obtained. Analysis can be done by using an apparatus known as ‘bomb calorimeter’ to obtain the heating value. Lower Heating Value (LHV) can be defined as total energy generated from combustion less heat of condensation of water vapour. LHV is also known as net calorific value. Higher Heating Value (HHV) is referred to gross heat released when a small bone-dry sample of material at standard state is burned in a test calorimeter at the reference temperature (25°C). The HHV is not realistic for WtE plant design calculations as HHV has included the heat of condensation of water vapour formed in the combustion reaction. Table 2.5 presented approximate net calorific values for some common MSW.
Table 2.5: Net calorific values of waste (John, 2005)

<table>
<thead>
<tr>
<th>Component</th>
<th>Net Calorific Value (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food waste</td>
<td>13</td>
</tr>
<tr>
<td>Paper</td>
<td>16</td>
</tr>
<tr>
<td>Plastics</td>
<td>35</td>
</tr>
<tr>
<td>Textiles</td>
<td>19</td>
</tr>
<tr>
<td>Rubber</td>
<td>26</td>
</tr>
<tr>
<td>Garden trimming</td>
<td>13</td>
</tr>
<tr>
<td>Wood</td>
<td>17</td>
</tr>
<tr>
<td>Tetra pack</td>
<td>22</td>
</tr>
<tr>
<td>Leather</td>
<td>18</td>
</tr>
<tr>
<td>Glass</td>
<td>0</td>
</tr>
<tr>
<td>Metals</td>
<td>0</td>
</tr>
</tbody>
</table>

If incoming waste exceeds an average of 7 MJ/kg of net calorific value, then WtE incineration should be considered. Waste with high calorific value (typically has a LHV above 16 MJ/kg) is suitable for WtE incineration. High calorific waste such as dry wood waste can burn without supporting fuel.

Table 2.6: Calorific value of Malaysia MSW (National Solid Waste Management Department, 2013)

<table>
<thead>
<tr>
<th></th>
<th>As Discarded</th>
<th>As Disposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher Heating Value, $HHV_{dry}$, kJ/kg (kcal/kg)</td>
<td>21,671 (5,176)</td>
<td>21,185 (5,060)</td>
</tr>
<tr>
<td>Lower Heating Value, $LHV_{wet}$, kJ/kg (kcal/kg)</td>
<td>6,850 (1,660)</td>
<td>6,325 (1,511)</td>
</tr>
</tbody>
</table>

Table 2.6 showed the calorific value, also known as ‘average higher heating value’ of MSW in Malaysia. Calorific value of Malaysia’s MSW is lower than calorific value of MSW in developed countries due to huge portion of organic waste in waste composition. The $HHV_{dry}$ of MSW as disposed at landfills is 21.185 MJ/kg while $LHV_{wet}$ is 6.325 MJ/kg. Net calorific value of MSW in Malaysia as discarded is 6.95 MJ/kg while net calorific value of MSW as disposed is 6.325 MJ/kg, which means MSW in Malaysia is not suitable for WtE incineration. This due to habit of Malaysians...
who like to mix all household wastes when throwing. Waste separation is needed to sort out the waste with high calorific value so that WtE incineration can be implemented.

2.3.8 Waste Management Options in Malaysia

2.3.8.1 Incineration

Incineration technology has been implemented in Malaysia but only with small scale. Until year 2015, there are 4 operating mini incinerators for MSW in Peninsular Malaysia. Mini incinerators are installed on the island and highland where collection and transportation of MSW is inconvenient. However, not all mini incinerators are operating due to high operating cost and technical problems in maintenance of the mini incinerators. There are a few waste incineration plants installed in Sabah and Sarawak. Figure 2.8 showed location of incinerators in Peninsular Malaysia.

![Incinerators in Peninsular Malaysia](JPSPN, 2012)

Figure 2.8: Incinerators in Peninsular Malaysia (JPSPN, 2012)

A few years ago, Malaysia government had proposed to install an incinerator in Broga, Semenyih area to dispose the MSW from Klang Valley. The residents brought forward their complaints to the court to ban the installation of incinerator at their place. As a result, the project was forced to be terminated. Construction of an incinerator in Taman Beringin, Kepong also faced strong opposition from the residents due to
NIMBY syndrome. Currently, disposal of hazardous and clinical wastes is mainly using incineration option where 100% of them are being incinerated (Hamatschek, 2010).

2.3.8.2 Landfilling

The most common solid waste disposal method in Malaysia is landfilling since it is the most economical one. There are 2 types of landfill which is sanitary landfill and non-sanitary landfill. Sanitary landfill is an engineered land disposal site for solid wastes which consists of i) impermeable base liner system, ii) leachate collection and treatment plant, iii) landfill gas management system, iv) emergency containment facility, and v) buffer zone to minimize the environmental impacts. Open dumping still occurred in Malaysia. Usually, low-lying land and swamp lands will be selected as landfill sites. Other than that, several old tin mines have been utilized for MSW disposal.

There are 163 operating landfills throughout entire Malaysia but only 17 of them are sanitary landfills with 10 in Peninsular Malaysia and 7 in East Coast of Malaysia. In addition, there are 131 closed landfills. These landfills need post closure treatment where monitoring and management will be required for the next 30 years. In general, the size of operating and closed landfills made up 0.01% of total land area of Malaysia (Nagapan, 2012).

Table 2.7: Number of landfills in Malaysia (JPSPN, 2012; NREBS, 2013; MHLG, 2013)

<table>
<thead>
<tr>
<th>States</th>
<th>Operating Landfills</th>
<th>Operating Sanitary Landfills</th>
<th>Closed landfills</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulau Pinang</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Perlis</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Kedah</td>
<td>8</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Perak</td>
<td>14</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>WP Kuala Lumpur</td>
<td>0</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Selangor</td>
<td>7</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Negeri Sembilan</td>
<td>7</td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>
Table 2.7: (Continued)

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>0</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melaka</td>
<td>12</td>
<td>2</td>
<td>23</td>
</tr>
<tr>
<td>Johor</td>
<td>16</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>Pahang</td>
<td>8</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Terengganu</td>
<td>11</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Kelantan</td>
<td>41</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>Sabah</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>146</td>
<td>17</td>
<td>131</td>
</tr>
</tbody>
</table>

2.3.9 Challenges of Solid Waste Management in Malaysia

Malaysia lacks the capacity necessary to effectively implement the existing waste management policies, guidelines and standards (Gregory, 2011). From the simple informal policies such as ABC 1998, waste management policies in Malaysia have evolved to supplementary provision in legislation, for example Local Government Act 1976 and Environmental Quality Act 1974, as well as formal policies such as the NSP 2005, MWM in 2006, NSWM Policy 2006 and SWMA 2007 (Agamuthu & Dennis, 2011). For example, the SWM and 3R policies that have been implemented in Malaysia, SWOT analysis shows that the weaknesses these policies are due to shortage of: a) advanced technologies, facilities and infrastructure, b) political will in enforcement and implementation, c) economic beneficial in term of incentives, d) capacity building, and e) government’s involvement in purchasing of recyclables (Agamuthu & Dennis, 2011).

Although policies have been implemented, targets may not be reached because lack of technical expertise and financial resources. There have been delayed in reiving the designated funding. Thus, implementation of the solid waste management plan will be obstructed. On the other hand, technical capability among solid waste management practitioners is still low. As a result, Malaysia is not able to plan, design, construct and manage own waste facilities.
Currently, Malaysia does not have enough waste facilities. Only small quantity of the proposed waste facilities have been approved due to constraint in fund and public objection on the location of the facilities to be installed. Some of the existing facilities are poorly operated due to limited manpower and technical expertise.

Generally, environmental awareness among Malaysian is considered low. 3R campaign has been launched to promote recycling activities but it has not resulted great positive impacts on waste management in Malaysia (Samsudin & Mashitah, 2013). Environmental education should be started at school level. There is a need to emphasize concept of environmental protection to the children so that they grow up as people who concerned about the environment.

There are gaps in existing data management practices on solid waste in Malaysia such as lack of proper data system and complication in data handover. Different types of waste fall under responsibility of different ministries and agencies. It is hard to gather the complete data. Furthermore, monitoring and data collection do not exist for every component in waste management.

Recyclables market in Malaysia is unregulated and unmonitored. The market demand for recyclables from the waste stream is being failed to be tracked and evaluated. As a result, economic potential of the recyclables is always undervalued. In addition, the recyclables market is dominant by certain companies. Those companies usually buy in the recyclables at very price.
2.4 Waste-to-Energy

2.4.1 Waste-to-Energy Technology

Incineration is a thermal treatment for the solid waste that involves combustion. Incineration is able to reduce the waste volume up to 90% and mass of waste up to 70%. It can help to save the landfill space. Waste-to-Energy (WtE) technology utilize solid waste for heat recovery, steam production and power generation through various conversion methods, thus it provides an alternative source of RE (Jake, 2011). The most common and widely used waste-to-energy technologies are incineration in a combined heat and power plant (CHP) as CHP consists of various advantages in terms of power generation. It is able to support the main electrical equipment and certain statements in network. Figure 2.9 showed a typical Waste-to-Energy.

![Image of Waste-to-Energy Diagram](Thomas, 2014)

Solid waste is delivered as feed stock to trash storage bunker. Solid waste will be lifted by the overhead crane to combustion chamber. When the waste is combusted, heat is being released and turned the water in boiler into steam. The high-pressured steam will move the blades of turbine generator to generate electricity. During post
combustion, gas and slug or ashes are produced as well (Zaman, 2010). Next, flue gases will be cleaned by different absorbers and filters of the pollution control system. After that, clean gas and water vapour are released through the chimney. The captured fly ashes will fall into hoppers and then being sent to the ash discharger by ash conveyor system. The wetted fly ashes are mixed with the bottom ash (from the grate). Finally, collected ashes are being sent to landfill for disposal. Instead to dispose the ashes, they can be used in road construction, concrete production or utilized in agriculture.

There are a few types of WtE technologies. The thermal technologies include: i) direct combustion, ii) pyrolysis iii) conventional gasification, and iv) plasma arc gasification.

i) Direct combustion – Direct combustion is a traditional technology to treat solid waste consisted of different types of incinerator such as fixed grate, fluidized bed, moving grate and rotary-kiln. The process involves direct combustion of the MSW with presence of oxygen-rich environment, typically at temperatures 700°C - 1,350°C to oxidize the waste and convert to CO₂, water and non-combustible materials with solid residue (Tan, 2013; Zaman, 2010). Generally, a WtE combustion plant will have net electrical efficiency of 15 – 25%, mainly depend on the plant size and conditions of steam. If the WtE plants export heat and/or electricity, 30% of efficiency can be achieved without input of external heat source. Thermal efficiencies more than 30% are possible in CHP configurations with only electrical energy is generated for process use where the heat is released to atmosphere (WSP Environmental Ltd, 2013).

ii) Pyrolysis – Pyrolysis is a process of thermo-chemical decomposition of organic material in the absence of oxygen to produce syngas, liquid (pyrolysis oil or liquid hydrocarbon) and solid (charcoal, unconverted carbon or ash) (Zaman, 2010). The process generally occurs at temperature 400°C-1000°C. There are multiple pyrolysis
technologies such as conventional pyrolysis, flash pyrolysis, vacuum pyrolysis, pressure carbonization and carbonization (Thomas, 2014). The syngas and pyrolysis oil can be directly used as boiler fuel. Refinery can also be done to obtain higher quality oil which can be utilized as adhesives, chemicals, engine fuels or other products (Thomas, 2014).

iii) Conventional gasification – Gasification is a process to produce syngas through heating of MSW with restrained quantity of oxygen. This process typically takes place at temperature of 760°C-1,500°C. The oxygen deficient atmosphere is able to prevent formation of harmful dioxins and furans. Syngas contains hydrogen, carbon monoxide, carbon dioxide, methane and water vapour that can be used to produce energy. The syngas can be utilized for power generation, heating or as a chemical feedstock after processing. The purpose is to remove water vapour and other trace contaminants. The amount of by-products (char/ash) produced will be approximately 15%-20% by weight of the input feedstock (Tan, 2014).

iv) Plasma arc gasification - Plasma arc gasification is a process of utilizing a plasma arc or plasma torch with the use of copper, tungsten, carbon electrodes, zirconium or hafnium to initiate the temperature for gasification reaction (Thomas, 2014). This process typically occurs at extremely high temperatures. The temperature plasma torches and arcs can range between 2,200 °C – 11,000 °C. It utilizes an electric current that passes through the air to create plasma which converts the waste into syngas (Tan, 2014). It is able to convert incinerator ash and other waste products into non-hazardous slag. Plasma arc gasification is said to have higher efficiency in converting solid waste to electricity due to its extremely high temperature, high heat density and nearly 100% conversion of carbon-based materials to syngas as compared to conventional pyrolysis and gasification technologies. Plasma arc gasification facilities require high capital and
operational costs. Hence, it is mostly used to treat hazardous waste but not commercially proven to treat MSW (Tan, 2014).

2.4.2 Waste-to-Energy Policies in Other Countries

Many countries have adopted their specific Waste-to-Energy (WtE) technologies based on regional differences and waste characteristics (Nickolas & Charles, 2013). Each country has implemented its own policies and government incentives on WtE. Sweden is very successful in WtE implementation and has become the global leader in energy recovery from waste (Swedish Avfall Sverige, 2013). Approximately 32 Swedish WtE facilities had treated 2,173,000 tons of household waste and 2,497,830 tons of industrial and other wastes in year 2009 (Williams, 2011). The incineration of waste provides heat for 810,000 homes and generates electricity for the use of 250,000 homes (Swedish Avfall Sverige, 2013). Sweden has a series of policies which are favourable to WtE, for example Sweden imposes carbon tax. Household waste in Sweden is also taxed since there is about 12.6% of carbon content by weight in waste. The carbon tax imposed fossil fuels is many times higher than the household waste. Furthermore, high landfill taxes and tipping fees encourage recycling and WtE because it is so expensive to dispose waste at the landfills. Landfilling of combustible waste and organic waste had been banned in Sweden at year 2002 and 2005 respectively. WtE power generators can get higher paid for the electricity generated since electricity price in Sweden is considered to be very expensive. Sweden has set a goal by year 2020 to achieve 50% of electricity generation from renewable sources (Williams, 2011).

Several polices had been issued by China to develop WtE technologies as an environment-friendly treatment method for MSW. The most representative was the grid electricity pricing’ where subsidy of US$ 30 per MWh of electricity will be paid to WtE power plants that generate less than 280 kWh/tonne of MSW (Nickolas & Charles,
The Renewable Energy Law 2006 had been enforced as the first and only legislation that to give support and strong legal protection for RE development. China government decided to deal with solid waste to improve the waste separation, recycling system and recovery system under National 12th Five Year Plan (2011–2015) (Xu et al., 2016). Large scale of waste incineration projects achieved rapid development of incineration projects in China since year 1988 when the first the incineration power plant was established. Until 2013, there were 166 of MSW incineration plants in China. Government had upgraded the standard for pollution control on MSW incineration since July, 2014 to favour the incineration industry development in China (Xu et al., 2016).

Economic growth in Thailand due to rapid growth in population and fast industrial expansion, energy consumption becomes a serious problem. In year 1992, ‘Energy Conservation Promotion Act’ and ‘Energy Conservation Fund’ were formed in order to tackle the energy problems. In addition, policies based on investment subsidy mechanism for promoting and increasingly use of RE were introduced by government. The new Ministry of Energy was set up and review these RE policies in October, 2002 (Prasertsana & Sajjakulnukitb, 2005). Thailand was the first nation to adopt FiT for renewables in ASEAN in year 2006. The added a premium to the wholesale electricity (adder) price for MSW was 2.50 Baht/kWh and the guaranteed premium period was 7 years. Currently, Ministry of Energy targeted 4,390 MW of power generation in Thailand from biogas, biomass and MSW while 160 MW of RE was expected to generate from MSW in Alternative Energy Development Plan (AEDP 2012 - 2021). Solar and wind energy had great potential to generate 3,200 MW while hydro was expected to generate 1,608 MW of RE. According to AEDP 2012 – 2021, WtE seemed to be one form in the national energy policy (Siriporn & Alice, 2015). WtE in Thailand consisted of 6 technologies which are: i) incineration, ii) refuse derived fuel (RDF), iii) biogas production by anaerobic digestion, iv) pyrolysis, v) gasification, and vi) landfill...
gas recovery (Siriporn & Alice, 2015). Until March, 2016, there were about 31 projects (2 GW) had signed a power purchase agreement (PPA) with the Electricity Generation Authority of Thailand (EGAT) (Understanding the Thai renewable energy market, 2016). Potential operators who lack of investment funding will be given investment assistance by Board of Investment in the form of investment incentives. MSW is one of the 3 types of RE project that can apply for investment grant allocated by the government for Design, Consultant and Partial Investment besides biogas and solar projects. The incentives also include 8-year corporate income tax exemption with another 50% reduction for the 8th to 13th years in corporate tax bill, as well as waiver of machinery import tariff (Department of Alternative Energy Development and Efficiency, 2017).

In India, Waste-to-Energy policy was announced by Gujarat government in 2016 is aimed to facilitate and promote utilization of MSW as renewable source in electricity generation, to promote disposal of MSW in a more environment friendly manner, to increase the efficiency and effectiveness of MSW collection and disposal, as well as to reduce the requirement of lands for MSW disposal. Under the policy, land on lease will be provided to business entities who wish to set up their solid waste power plants by urban local bodies at a token rate of Rs 1 (Government of Gujarat, 2016). In addition, civic bodies will bear the stamp duty on the leased land. Besides, the power plant will be free from imposed tax (Government of Gujarat, 2016).
2.4.3 Potential of Waste-to-Energy in Malaysia

Many countries have successfully implemented WtE especially the developed and high-income countries. WtE sector is growing in developing countries as well. Malaysia is blessed with various RE resources, for example biogas, biomass, geothermal, small hydro, solar, tidal and wind but not yet fully explored and developed. In fact, Malaysia has plenty of biomass and wood waste resources available for immediate exploitation. Most of them are readily available waste from agricultural sector (Azman et al., 2011). Currently, agriculture wastes to energy technologies have been significantly implemented in Malaysia. The main agriculture waste for energy conversion will be palm oil biomass due to generation of huge amount, banning on agriculture open burning and lack of landfill space. The world’s second largest producer of palm oil is Malaysia. Currently, palm oil biomass has been used as bio-energy, as well as green chemical such as bio-polymers, bio-fertilizer and bio-composites. There are more biomass resources to be exploited in all regions of Malaysia especially at rural areas. Agriculture biomass waste-to-energy technologies that are commonly used are energy recovery by incineration and biogas production by anaerobic digestion. In order to promote utilization of biomass, various policies and actions had been introduced by government of Malaysia including:

i) National biotechnology policy – Convert biomass into liquid fuels and high value.

ii) Green technology policy – Financing scheme and investment tax incentives for green.

iii) Palm oil industry biogas power generation – Electricity generation via biogas from palm oil mill effluent supplied to national grid.

iv) Biomass industry strategic action plan - Promote high value utilization of biomass by small and medium companies.
v) National biomass strategy - Develop of market and technology for biomass pallets and biochemical.

vi) National Biomass Strategy 2020 - An approach to create new wealth creation for Malaysia’s palm oil industry by assessing revenue potential revenue from palm oil through utilisation of biomass.

WtE technologies can be the solution for Malaysia’s increasing waste generation and energy demand challenges, as well as reduction of GHG emissions. With the installation of WtE technologies, solid waste can be converted into energy. The steam produced can be used in industry while power generated can be sold to electricity grid. Malaysia government is actively promotes the use of RE since RE resources have been added as the 5th fuel in the mix of energy supply. Solid waste becomes one of the renewable sources. SEDA Malaysia has a target to increase renewable energy capacity up to 2,080 MW by 2020 and 360 MW of the renewable energy is expected to generate from solid waste (Ministry of Energy, Green Technology and Water, 2011). In order to achieve target set by the government, WtE incineration plants with design that suit Malaysian solid waste characteristics should be installed as landfill space is becoming limited and it is difficult to open new landfill due to land scarcity.
2.5 Electricity Energy Status in Malaysia

2.5.1 Electricity Generation

Energy is very important to support a country’s socio-economic development especially for Malaysia as it depends largely on energy resources, especially natural gas and crude oil for its economic growth (Chong et al., 2015; Tan et al., 2013). Demand for electricity in Malaysia is always growing along with population and income growth (Tan et al., 2013). Both conventional and renewable sources of energy contribute to power generation in Malaysia. Figure 2.10 indicated sources of energy contribute to electricity generation in Malaysia of year 2015. Annual electricity generation of Malaysia in year 2015 is 144,565 GWh which has increased 0.513% from 143,827 GWh of the previous year.

In 2015, fossil fuel resources such as natural gas, coal, oil and diesel supplied approximately 90% of Malaysia’s electricity output. Natural gas had become main source in electricity generation in 2015 at 66,919 GWh which is 46.3%, followed by coal at 59,335 GWh which is 41.0% and hydro at 15,524 GWh which is 10.7% of the total generated electricity. A very small portion of electricity which is only about 0.9%
is generated by other sources which referred to renewable sources such as biomass, solar and biogas.

2.5.2 Energy Policies

Electricity sector has gained rapid development in the past few decades along with economic growth in Malaysia, especially in manufacturing and industrial sectors. Electrical energy sold in 1949 was only 141.3 GWh. By 2007, there was more than 89,000 GWh of electric energy being sold (Thahirah & Bodger, 2010). Generally, electricity energy related policies in Malaysia are formulated by Ministry of Energy, Green Technology and Water, Energy Commission, Economic Planning Unit and Malaysia Energy Centre.

First policy related to energy sector was formulated in 1974. The national oil company (PETRONAS) was established under Petroleum Development Act 1974. In order to regulate the petroleum industry, National Petroleum Policy 1975 was then implemented under 3rd Malaysia Plan (1976–1980). There would be some effects on fuel resources that supplied to the electricity sector though these policies did not govern the electricity sector directly (Thahirah & Bodger, 2010). The policy that really governed electricity energy sector in Malaysia was National Energy Policy 1979. Later various policies were formulated to support its implementations. On the next year, National Depletion Policy 1980 was introduced followed by Four Fuel Diversification Policy 1981. To avoid over-dependence on oil as the main energy resource was the main objective for the introduction of Four Fuel Diversification Policy. During the 7th Malaysia Plan (1996–2000), ensuring sufficient generating capacity and upgrading infrastructure for electricity transmission & distribution became the main objectives for electricity sector. The Four Fuel Policy originally focused on oil, gas, coal and hydro was amended to become Fifth Fuel Policy in year 2000 under 8th Malaysia Plan (2001–
2005) to add renewable energy (RE) as the fifth fuel in the mix of energy supply. By year 2005, RE was targeted to contribute 5% to the total electricity demand in Malaysia by year 2005 (Sumiani & Roozbeh, 2012).

The policy of the 8th Malaysia Plan was continued in the 9th Malaysia Plan (2006-2010) to strengthen the initiatives for RE projects so that targeted grid-connected RE generation of 350 MW can be achieved by year 2010 but government goal was not achieved though Malaysia applied acceptable efforts to develop RE (Sumiani & Roozbeh, 2012). 10th Malaysia Plan (2011-2015) mentioned establishment of stronger incentives for investments in RE sector. Malaysia is blessed with various RE resources including solar, biomass, biogas, biogas and mini-hydro. In the 11th Malaysia Plan (2016-2020), the focuses are given on promoting new RE sources for the enhancement of RE capacity. Also, net energy metering (NEM) was implemented to boost the development of RE. Under the 11th Malaysia Plan, new RE sources such as geothermal, ocean and wind energy will be explored through studies in order to diversify the generation mix (EPU, 2015). The potential of geothermal energy is being explored. There is a 12km² of geothermal field being discovered in Apas Kiri, Sabah. Since geographical location of Malaysia is being surrounded by sea, study will be done to determine viability of ocean energy. Currently, national wind mapping activities are going on as well to survey the feasibility of wind energy (EPU, 2015). Sabah had enabled self-consumption for solar PV system users while the excess electricity generated will be sold to the utility companies in order to encourage public and manufacturing facilities for generating more RE.
2.5.3 RE Policy

Feed-in Tariff (FiT) policy stated that all renewable power utilities must be purchased for sale and in return to receive a premium - The prices (tariffs) were set by government through long-term contracts (Huang & Wu, 2011). France, Germany, Canada, Belgium, China, Denmark, United Kingdom, Kenya, Italy, Switzerland, Thailand and many other countries where minimum of 50 countries and 25 states or provinces worldwide started to adopt FiT mechanism by early 2010 (Ministry of Energy, Green Technology and Water, 2011). Experience from around the world suggests that the most effective policy in encouraging rapid and sustained deployment of renewable energy was FiT (Toby & Yves, 2009).

In Malaysia, tariff for RE has been introduced since year 2001 under Small Renewable Energy Program (SREP). However, investors were not interested to invest due to high tariff rate for solar and wind whereas investment for biogas and biomass did not gain much success as well, even with low tariff rate (Haslenda & Ho, 2011). New FiT for improving the previous tariff had been started officially after passing of Renewable Energy Act 2011 and SEDA Malaysia Act 2011. The FiT system obliged distribution license (DL) to set the FiT rate for buying RE generated from feed-in approval holder (FIAH) for a specific period. DL was referred to companies that hold the licence to distribute electricity in Malaysia such as TNB, Sabah Electricity Sdn Bhd and NUR Power Sdn Bhd. FIAH can be individuals, companies or industries that hold feed-in approval issued by SEDA Malaysia. The FiT rate in Malaysia was not fixed where it depended on type and characteristic of renewable energy technologies as well as installed capacities. For example, the duration for biomass and biogas is 16 years while for small hydro and solar PV is 21 years.
Figure 2.11: Composition of power generation of commissioned RE installations 2016 (SEDA Malaysia, 2019)

Figure 2.11 showed the composition of power generation from commissioned renewable energy installations under Malaysia’s FiT system in year 2016. Under the FiT system, total amount of power generated by commissioned RE installations in year 2016 is 419,767.14 MWh. Solar PV contributes about 44.81% which is 188110.78 MWh in power generation followed by biomass as the second largest contributor which produces 132058.28 MWh (31.48%) of power. Biogas from landfill and agriculture waste contributes 8.98% while solid waste contributes 5.34% in generation of power by commissioned RE installations. Small hydro which is different from the hydro power station also generates 31450.36 MWh of power. Though there is no contribution from geothermal energy so far, Malaysia’s first geothermal power plant in Sabah’s east coast is set to start operations by June, 2018. This geothermal power plant in Tawau is projected to add 30 MW to Sabah’s grid (Malaysia’s first geothermal power plant to open in Tawau, 2016).

SEDA Malaysia targeted to increase RE capacity up to 2,080 MW by 2020. 240 MW of RE is expected to generate from biogas, 800 MW from biomass, 360 MW from solid waste, 490 MW from small hydro while 190 MW from solar PV. By 2030, RE
capacity is expected to reach 4,000 MW through implementation of FiT mechanism (Ministry of Energy, Green Technology and Water, 2011). Table 2.8 presented the cumulative RE capacity targets of Malaysia in unit MW.

Table 2.8: Cumulative RE Capacity Targets of Malaysia in MW (Ministry of Energy, Green Technology and Water, 2011)

<table>
<thead>
<tr>
<th>Year</th>
<th>Biogas</th>
<th>Biomass</th>
<th>Solid Waste</th>
<th>Small Hydro</th>
<th>Solar PV</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>100</td>
<td>330</td>
<td>200</td>
<td>290</td>
<td>65</td>
<td>985</td>
</tr>
<tr>
<td>2020</td>
<td>240</td>
<td>800</td>
<td>360</td>
<td>490</td>
<td>190</td>
<td>2080</td>
</tr>
<tr>
<td>2025</td>
<td>350</td>
<td>1190</td>
<td>380</td>
<td>490</td>
<td>455</td>
<td>2865</td>
</tr>
<tr>
<td>2030</td>
<td>410</td>
<td>1340</td>
<td>390</td>
<td>490</td>
<td>1370</td>
<td>4000</td>
</tr>
</tbody>
</table>

2.5.4 Biomass as Potential RE

Malaysia has plenty of biomass resources. There is massive amount of biomass generated from agriculture sector in Malaysia. Most of the biomass is from plantation and agricultural residues. The major biomass waste in Malaysia consists of oil palm waste, rice, sugarcane waste and coconut trunk fibres. The highest amount of biomass is contributed by oil palm sector since Malaysia is one of the largest palm oil producers worldwide after Indonesia. Malaysia exported more than 19.9 million tonnes of palm oil in year 2017 resulting in generation of more than 80 million tonnes of oil palm biomass. Palm oil industries generate OPF, OPT, EFB, PKS, MF and POME as by-product which can be converted to energy. Currently, primary approach to generate electricity from biomass is through combustion like burning the EFB, PKS and MF in boilers to produce high-pressured steam to move the turbine to generate electricity. POME can be treated using anaerobic digestion to be converted into biogas. The biogas can be used for heating or cooking, converted to mechanical work or electricity and act as a synthetic gas to produce higher quality fuels. Approximate 15 billion m$^3$ of biogas is estimated to be produced by 58 million tonnes of POME annually across Malaysia. Rice husk is also an important biomass resource with high potential for biomass cogeneration. At Perlis
state, there is biomass power plant which utilizes rice husk to generate 10MW of power (Biomass resources in Malaysia, 2018).

Biomass resource definitely has great potential to act as a sustainable source of RE in Malaysia since 11% of the Gross National Income is generated from agricultural sector. Utilization of biomass as source of RE can help to reduce dependency on fossil fuel in generating electricity, thus reducing greenhouse gases emission to atmosphere. In year 2018, 30 MW installed capacity has been allocated to biomass category while 5.9 MW of installed capacity has been allocated to biomass-solid waste category under FiT system according to SEDA Malaysia. Large-scale investment and advanced technologies are required to convert biomass to energy efficiently and economically (Biomass resources in Malaysia, 2018).

2.6 Greenhouse Gases Emission in Malaysia

Climate change is a worldwide issue. Excessive GHGs emission contributes to climate change. Malaysia is still on track to reduce GHGs emission significantly in mitigating climate change. In year 2011, the net GHGs emission of Malaysia was 27,284 Gg CO\textsubscript{2} eq after accounting for removal of 262,946 Gg CO\textsubscript{2} eq from 290,230 Gg CO\textsubscript{2} eq of total GHGs emission as reported by Ministry of Natural Resources and Environment. The Malaysian greenhouse gas inventory covers 3 major GHGs which are CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O. CO\textsubscript{2} contributed the largest share which was 72% in Malaysia’s greenhouse gases emission, followed by CH\textsubscript{4} accumulated for 23% and 5% of N\textsubscript{2}O. Other greenhouse gases such as HFC, PFC and SF\textsubscript{6} were comparatively insignificant with the massive amount of CO\textsubscript{2} and CH\textsubscript{4}. Figure 2.12 showed the trend of greenhouse gases emission in Malaysia from 1970 to 2010.
There was continuous increase in the GHGs emission from 1970 to 2010 especially for CO₂. The drastic increase in CO₂ emission from year 1990 to 2008 was due to rapid industrialization in Malaysia. In year 2009, Malaysia set a target to reduce more than 40% GHGs emission intensity of its GDP compared to 2005 levels by year 2020. Various policies and actions were implemented under the 10th Malaysia Plan (2011-2015). Malaysia succeeded to achieve 33% of reduction by the end of year 2013 and pledged to further reduce 45% by year 2030. Figure 2.13 showed Malaysia’s greenhouse gas emission by sector in year 2011.

Figure 2.13: Malaysia’s greenhouse gas emission by sector in year 2011 (Ministry of Natural Resources and Environment Malaysia, 2015)
Energy sector contributed the most to Malaysia’s GHGs emissions at 76%, followed by waste sector at 12%, industrial processes at 6%, agriculture sector at 5% and LULUCF at 1%.

Figure 2.14 and 2.15 reported the major sources of carbon dioxide and methane emissions.

Figure 2.14: Sources of CO₂ emission in Malaysia (Ministry of Natural Resources and Environment Malaysia, 2015)

In year 2011, there was a total 208,258 Gg of CO₂ emitted. Energy industries emitted the highest CO₂ emission as fuels were used to generate electricity, to run petroleum refining and natural gas transformation processes which made up 55% at 113,567 Gg CO₂. Emission of CO₂ from transport was the second highest which accounted for 21% at 44,007 Gg CO₂ because car ownership in Malaysia was very high. 11% of CO₂ was emitted by manufacturing industries and construction at 23,004 Gg CO₂.
In year 2011, CH$_4$ emission was reported as a total of 67,532 Gg CO$_2$eq. The highest emission came from solid waste disposal sites which made up about 46% as decomposition of MSW at landfills under anaerobic conditions will generate huge amount of landfill gas (LFG) that contains 50–60% methane and 30–40% carbon dioxide by volume. Fugitive emissions natural gas and oil were also main source of CH$_4$ which contributed 44% of the total emission. Other sources such as palm-oil mill effluent and rice cultivation covered approximately 10% of total CH$_4$ emission.

### 2.6.1 GHG from Waste

In Malaysia, the highest CH$_4$ emission is emitted by waste sector. The most common method of waste disposal in Malaysia is landfiling. Figure 2.16 showed CH$_4$ emission from landfills in different states of Malaysia at year 2011.
Approximate 330 Gg of methane gas was emitted in year 2011 by the landfills across Malaysia. High CH\textsubscript{4} emission was coming from well-developed states like Penang, Johor and Selangor with rapid urbanization which contributed to increasing amount of waste generation. Correspondingly, higher methane emission from landfills and open dumpsites at states in Northern region such as Penang, Perak and Kedah could be due to lack of sanitary landfills in Northern region. Non-sanitary landfills are not equipped with proper linings and gas collection system to prevent emission of methane into the atmosphere. The efficiency of landfill gas collection is still rather low even in sanitary landfills that equipped with those systems. Besides, methane emission from the Southern region (Malacca, Johor) and Central region (Selangor, Kuala Lumpur, Negeri Sembilan) were mainly coming from sanitary landfills as there were more sanitary landfills in these regions. There was no landfill in Labuan, thus no methane emission data was recorded.
2.6.2 Potential of RE to Reduce GHG Emissions

Malaysia is blessed with various RE resources including biomass, solar, biogas, and mini-hydro. Biomass and solid have great potential to be utilized as sources of RE. The use of RE in Malaysia is able to avoid significant CO$_2$ emission. This is because majority of the CO$_2$ emission in Malaysia is contributed by electricity and heat production sector. Fossil fuel power plants are widely used to generate electricity, causing an increase in the main byproduct of fossil fuel burning, which is carbon dioxide. By displacing generation of electricity from conventional fossil fuels with other RE sources, emission of the major GHG which is CO$_2$ can be reduced significantly. Moreover, the CH$_4$ emission from landfills can also be reduced as the amount of biomass and solid waste being disposed become less since they have been utilized for electricity generation.

Table 2.9 presented the annual CO$_2$ avoidance with commissioned RE installation in power generation based on SEDA Malaysia. The annual CO$_2$ avoidance increased with an increasing of commissioned RE installation from year 2014 to 2018.

Table 2.9: Annual CO$_2$ avoidance in power generation with commissioned RE installation (SEDA Malaysia, 2019)

<table>
<thead>
<tr>
<th>Year</th>
<th>Biogas (Landfill / Agri Waste)</th>
<th>Biogas (Solid Waste)</th>
<th>Biomass</th>
<th>Biomass (Solid Waste)</th>
<th>Small Hydro</th>
<th>Solar PV</th>
<th>Geothermal</th>
<th>CO2 Avoidance (tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>60173.28</td>
<td>299725.65</td>
<td>859748.75</td>
<td>66906.53</td>
<td>265280.19</td>
<td>999196.05</td>
<td>0.00</td>
<td>2550030.45</td>
</tr>
<tr>
<td>2017</td>
<td>54649.61</td>
<td>233448.73</td>
<td>797555.63</td>
<td>64081.87</td>
<td>239701.36</td>
<td>844463.36</td>
<td>0.00</td>
<td>2233901.45</td>
</tr>
<tr>
<td>2016</td>
<td>44438.77</td>
<td>110433.54</td>
<td>633369.22</td>
<td>50762.21</td>
<td>186067.79</td>
<td>559601.53</td>
<td>0.00</td>
<td>1586673.06</td>
</tr>
<tr>
<td>2015</td>
<td>34376.98</td>
<td>65120.72</td>
<td>526123.95</td>
<td>25403.50</td>
<td>155086.97</td>
<td>346944.32</td>
<td>0.00</td>
<td>1153056.44</td>
</tr>
<tr>
<td>2014</td>
<td>22654.80</td>
<td>36746.28</td>
<td>393387.12</td>
<td>12921.35</td>
<td>116856.57</td>
<td>165521.11</td>
<td>0.00</td>
<td>748087.23</td>
</tr>
<tr>
<td>2013</td>
<td>9011.95</td>
<td>14773.62</td>
<td>237311.61</td>
<td>9921.35</td>
<td>72317.31</td>
<td>39967.74</td>
<td>0.00</td>
<td>383303.58</td>
</tr>
<tr>
<td>2012</td>
<td>67.70</td>
<td>8008.79</td>
<td>92820.38</td>
<td>2231.82</td>
<td>17750.91</td>
<td>5003.58</td>
<td>0.00</td>
<td>125883.18</td>
</tr>
</tbody>
</table>
2.7  Life Cycle Assessment (LCA)

2.7.1  Life Cycle Thinking (LCT)

Now, consumers are getting interested what is going on to the world of the products while purchasing. Life cycle thinking (LCT) considers every person and process along the entire chain throughout life cycle of the product, from cradle to grave. Each person or process has a role and responsibility to hold, considering all relevant external effects. Therefore, while making decisions on policies, patterns and management strategies of production and consumption, the impact of all life cycle stages shall be overall considered. LCT has also been defined as using a series of reference data sources for identification of trends in results and conclusions that include LCA’s basic method without requiring detailed assessment of each process. Opportunities and risks of a product, service or technology from raw materials until disposal can be identified using life cycle method. To do this, life cycle thinking should be linked to a complete and systematic quantitative approach which known as life cycle assessment.

Life cycle thinking is necessary to addresses these life cycle-generated impacts by using different methods which aimed to minimize them such as i) Life Cycle Assessment - LCA, ii) Life Cycle Management - LCM, iii) Life Cycle Costing – LCC, and iv) Design for the Environment - DfE.
2.7.2 **Introduction to LCA**

Environmental impacts of a product or service are necessary to be quantified and compared for sustainable development. Tools and methods are required to complete this task. Life Cycle Assessment (LCA) is actually a methodology developed for evaluating the mass balance of inputs and outputs for a system, as well as organizing and converting those inputs and outputs into environmental categories or terms with relative to human health, resource use and ecological areas. Thus, LCA is used in analysing the environmental burden of products from cradle to grave within their entire life cycle from extraction of raw material to manufacturing and consumption until disposal or recycled (Guinee, 2002; Finnveden et al., 2009).

The LCA methodology is incorporated in international standards published by the International Organization for Standardization (ISO). LCA is defined as an equipment to evaluate the potential environmental impacts and resources used throughout the life cycle of a product (ISO, 2006).

The involved international standards are:

i) ISO International Standard 14040 - principles and framework  
ii) ISO International Standard 14041- goal and scope definition and inventory analysis  
iii) ISO International Standard 14042 - life-cycle impact assessment  
iv) ISO International Standard 14043 - life-cycle interpretation
According to ISO 14040: 2006, the application of LCA can assist to:

i) Identify chances for improving product’s environmental performance at different stages in their life cycle;

ii) Inform decision-makers in the public and private sectors in term of planning strategic, setting of priority, design or redesign of the product or process;

iii) Select the related parameters of environmental performance including techniques and measurements;

iv) Do marketing by implementing eco-labelling scheme to come out with an environmental product declaration or make an environmental claim.

2.7.3 Origin of LCA

In 1960s, LCA concept began as scientists were aware of fossil fuels depletion at fast rate. LCA was developed as a way to understand the impacts of energy consumption. A few years later, global-modelling studies were down to predict the relationship between demand for raw materials and energy resource with the world’s population changing effects. The first commissioned study of LCA was conducted for the Coca Cola’s company in the late of 1960s (Hunt & Franklin, 1996). Due to growing recognition on environmental impacts of disposable packaging, Coca Cola’s company and other early life cycle practitioners were interested to know environmental impacts associated with the production and disposal of different packaging options (Baumann & Tillman, 2004).

U.S EPA refined this methodology to create Resource and Environmental Profile Analysis (REPA) in the 1970s. In the late 1980s, solid waste issues gained global attention. Hence, the life cycle analysis method developed in the REPA studies
had been used to analyse the problem. For example, a LCA was completed covering comparison between paper and plastic grocery bags of in term of resource and energy consumptions, as well as impacts to the environment for the Council for Solid Waste Solutions in year 1999.

Different researchers carried out LCAs for similar products had produced conflicting results due to varying methodological choices during that time. Also, there was a doubt that the results of LCA could be easily modified and manipulated to generate preferable outcomes. Thus, the first SETAC-sponsored international scientific conference on LCA was being held in the year of 1990 where researchers and practitioners discussed on the standardization of LCA methodology. The term ‘LCA’ was coined in the conference. After that, SETAC’s Code of Practice published the first guidelines for LCA. These methodological standards were then further developed by International Organization for Standardization (ISO). By year 1997, ISO 14040 Life cycle assessment – Principles and framework was completed. The most recent version ISO 14044 Life cycle assessment – Requirements and guidelines was published in year 2006 where a few additional standards were developed and revised from ISO 14040:1997. Now, LCA has been widely used by public and private sectors to understand and concern towards environmental impacts arising from their actions.

2.7.4 LCA Principle and Framework

Based on ISO 14040, LCA consists of four phases: i) goal and scope definition, ii) life cycle inventory, iii) impact assessment, and iv) interpretation. Figure 2.17 explains the basic framework and order of LCA.
2.7.4.1 Goal and Scope Definition

Goal and scope definition is the first step in conducting LCA. It forms the foundation upon which the whole LCA study is laid upon (ISO, 2006). The goal of study includes objective of the assessment and identification of the product to be assessed. A statement of intended application of results and targeted audience can be mentioned in the goal of study.

The scope describes the boundary of study, which reflects the limit of study. Scope of study should define the functional unit, product system, system boundary, allocation procedure, selected impact assessment methodology, data requirement, assumption, data quality and limitation.

The functional unit (FU) is a measure of the targeted products or services within the studied system boundaries in quantitative term. FU is very important in LCA. FU has to be defined clearly. When defining the functional unit, it is based on the
performance of that particular product’s function. To fulfil the same need, different amount of products may be used. There may have a few possible functional units in a system but the selected one will be depended on the study’s scope and goal.

System boundary determines the processes’ unit to be included in the study. The relevant boundaries which can be considered are:

i) Boundaries between nature and technological system - A life cycle usually begins at the extraction of materials from the nature and ends with waste disposal.

ii) Geographical area - Electricity production, transport system and waste management are different from one region to another. Besides, ecosystems sensitivity to environment impacts also differs regionally.

iii) Time horizon - Assessment on present impacts and future scenarios are usually done in LCA. Time limit that set in the study can be influenced by the involved technologies, lifespan of the pollutants or other variables.

iv) Boundaries between current life cycle and related life cycles of other technical systems - Most activities are related to each other and can be separated for further study.

**2.7.4.2 Life Cycle Inventory**

The second stage of LCA is an inventory creation consists of all inputs and outputs of processes that occur during the life cycle of a product including phases of production, distribution, use and final disposal. To gather environmentally related data from the identified processes is the main purpose of inventory creation. LCI is a process to quantify the energy, resources and materials use, as well as atmospheric and waterborne emissions, solid waste and other relevant release during the whole life cycle
of a product or activity that included in the model of product system. Figure 2.18 showed stages and boundaries of life cycle assessment.

![Life Cycle Inventory Diagram]

Figure 2.18: Life cycle assessment stages and boundaries (ISO, 2006)

Data collecting is very important in this phase. The process of data collection can be very time-consuming. Sources of data are usually from the main producers and suppliers. Literature review and LCA database are also sources to get data for the creation of life cycle inventory. Generally, standard inputs such as electricity, materials and water will be selected from LCA databases. However, the input data found in the database mostly reflect European scenarios. Data for developing and under-developed countries is limited and unavailable (Green, 2002). All data should be related to the reference flow as defined by the functional unit. Two types of data are available. Background data is not specifically related to the product system and may consist of average or ranges; while foreground data is referred to the product system based on actual plant conditions and onsite measurements.

After gathering required data, each step in the product system should be analysed before certain calculation being made. Then, compiling the input and output data by performing computer modelling to clearly display the life cycle inventory.
2.7.4.3 Life Cycle Impact Assessment

The inventory table can be the result for a LCA study but it is difficult to interpret list of substances. Hence, quantification and assessment of the results from the inventory analysis will be done using Life Cycle Impact Assessment (LCIA) to identify the environmental significance (ISO, 2006). Thus, the interpretation of LCIA for the inventory results should clearly reflect potential impacts towards the environment in terms of human health, natural environment and natural resources (Guinee, 2002).

LCIA involves selection of impact categories. According to ‘Code of Practice’ by SETAC, the impact categories include: i) resource depletion (depletion of abiotic resources, depletion of biotic resources); ii) pollution (global warming, ozone depletion, human toxicity, eco-toxicity, photochemical oxidant formation, acidification and eutrophication); and iii) degradation of ecosystems and landscape (land use). Impact category indicator result can be divided into midpoint and endpoint level. Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category such as acidification, climate change, human toxicity and ozone depletion, prior to the endpoints, at which characterization factors or indicators can be derived to reflect issues of concern such as ecosystem quality, environment, human health and resources (Jane et al., 2000).

Generally, impact assessment consists of 4 stages.

i) Classification. All substances are sorted into classes according to their effects on the environment. For example, substances that contribute to the greenhouse effect and ozone layer depletion respectively are divided into two different classes. Besides, some substances can be included in more than one class.
ii) Characterization. The process of substances’ aggregation within each class produces a score. It is insufficient just to add up the quantities without applying weightings to the substances involved. The effects of substances may be differed from each other. Applying weighting factors to different substances can help in solving this problem.

iii) Normalization. Impact scores and resource consumptions are related to a common reference in this step. A common scale can be used to insert different impact scores and resource consumptions. Normalization step can be carried out to understand better of the relative effect’s size. A benchmark is set for each effect calculated for the entire product’s life cycle against the known total qualitatively.

iv) Valuation. Value is distributed in this stage to different impacts for allowing integration across all impact categories. The importance assigned to the various environmental impact and resource consumptions is reflected with ranking and grouping in this step. Policy or decision makers are able to compare directly and easily of the overall potential effect for the product after valuation is completed.

The assessment phases in the EDIP method for the environmental assessment of products are:

i) Classification - Process of assigning and aggregating from the inventory into relatively homogeneous impact categories.

ii) Characterization - Assessment of the magnitude of potential impacts on the chosen categories on resources depletion, human health, ecological health and other subcategories. Each of the categories can be further assessed into global, regional and local impacts.
iii) Normalization - Consumptions and impact potentials are quantified relative to a reference impact which functions as a common scale.

iv) Weighting - Assigning weights of importance to each impact so that the most important impact can be indicated to generate a single score of environmental impact. Decision makers can easy make comparison on different alternatives with different criteria.

Normalization and weighting are not a must in conducting LCA study, especially weighting step which is more subjected to preference of the LCA practitioner. It will be encouraged to take this step if comparative studies are to be done (ISO, 2006).

2.7.4.4 Interpretation

Interpretation of assessment outcomes is the final stage of the LCA process. Life cycle interpretation is a technique to check, evaluate, identify and present the findings from the LCA’s result. The output of this stage is to identify the most significant environmental impact category as well as the life cycle stage. Evaluation and identification of eco-efficiency opportunities can be done with interpretation to enable LCA becoming a tool for better achievement of economic and environmental performance in the products’ life cycle.

ISO has described objectives of life cycle interpretation as:
i) Analyze result, reach conclusion, explain limitation, provide recommendation and report the results.

ii) Present the LCA results clearly and comprehensively.

iii) Prepare a LCA report. Following elements should be found in the report:

a) Administrative information (name of practitioner, contact information, date of report)

b) Goal and scope definition

c) Life cycle inventory analysis (data collection and calculation procedures)

d) Life cycle impact assessment (methodology and impact assessment result)

e) Life cycle interpretation (limitations, assumptions, data quality, results)

f) Critical review (reviewer’s name and affiliation of reviewer, response to recommendation)

2.7.5 LCA Software

There are various tools for conducting LCA which support different applications and phases of LCA. A number of software are available and can be accessed through different platforms to perform LCA. Some are free but most of them are commercial. Most software comes with databases where some databases are more comprehensive than the others. Table 2.10 showed some existing LCA tools with descriptions.
<table>
<thead>
<tr>
<th>Software</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boustead Model</td>
<td>Boustead Model is commercial software developed by Boustead Consulting to model non-linear, complex systems without using approximations by utilizing a database of unit operations. The files are categorized into top data, core data and program files. Boustead Model contains extensive database which include fuels and energy, raw materials, as well as emission in the form of solid, liquid and gaseous. This software empowers user to manipulate the data in database and select own preferable method of presentation from a host of choices.</td>
</tr>
<tr>
<td>ECO-it - Eco-Indicator Tool for environmentally friendly design</td>
<td>ECO-it is a user-friendly commercial tool which costs cheaper price as compared to advanced tool such as Simapro. Its program structure is simple and easy to be used. Its input consists of four stages which are life cycle, production, use and disposal. The life cycle of a product can be modelled quickly and the result will show potential areas to be improved. The impact assessment methods used in ECO-it are CO₂ equivalents related to carbon footprint and eco-indicator point system based on the ReCiPe method.</td>
</tr>
<tr>
<td>EIOLCA - Economic Input-Output LCA</td>
<td>EIOLCA is developed by Green Design Institute of Carnegie Mellon University to estimate energy resources and materials required, as well as emissions to the environment that resulted from economy activities. Its procedure is using economic and environmental data to evaluate effect of manipulating output of a single sector. Industry transactions information which referred to purchasing of materials by one industry from other industries and data on environmental emissions of the industries are utilized to estimate the total emissions throughout the supply chain. Most data in database is from North American Industry Classification System (NAICS). Only limited number of environmental impacts is considered in this tool.</td>
</tr>
<tr>
<td>GaBi - Product Family (Ganzheitlichen Bilanzierung-holistic balancing)</td>
<td>GaBi is one of the two most commonly used LCA software developed by Five Winds International, University of Stuttgart (IKP) and PE Product Engineering. GaBi is a full service LCA-based software where a license is required to purchase in order to download the software. It contains the largest internally consistent LCA databases on current market and contains over 10,000 ready-to-use LCI profiles.</td>
</tr>
<tr>
<td>IDEMAT</td>
<td>IDEMAT is a tool developed by Delft University of Technology for selection of materials in a design process. It is equipped with database which includes technical information about materials, components and processes. The designers are able to make comparison on environmental impacts when choosing the materials and processes for their products. This tool can help them to design eco-friendly product in a convenient way. The database is made available at <a href="http://www.ecocostvalue.com">www.ecocostvalue.com</a> covering more than 1000 types of material, service, process, and end-of-life scenario. The LCI in IDEMAT dataset is developed by Delft University of Technology with reference to data from CES EduPack and Swiss Ecoinvent databases. This tool is available in both laptop and iPhone versions.</td>
</tr>
<tr>
<td>Software</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>KCL-ECO</strong></td>
<td>KCL LCA software is commercial software developed by VTT Technical Research Centre at Finland since 1992 with the version 4.1 currently in use. KCL-ECO allows the user to perform life cycle inventory (LCI) calculations, impact assessment calculations as well as present the calculation results in a comprehensible way through its unique reports and charts.</td>
</tr>
<tr>
<td><strong>LCAiT</strong></td>
<td>LCAiT software is developed by CIT EkoLogik (Chalmers IndustriTeknik) since 1992. LCAiT has been used for the environmental assessment of products and processes. It includes an impact assessment database, including characterization factors and weighting factor.</td>
</tr>
<tr>
<td><strong>openLCA</strong></td>
<td>openLCA is a free and open source software developed by GreenDelta for assessing and modelling life cycle of a product, process or service with a number of import and export options. OpenLCA is user-friendly, quick, allowing building of simple as well as complicated models. The software serves a good network and flow visualization. It also offers a high performance database management system on a local server. LCA data format is easy for import and export. openLCA software has powerful plug-in structure that allows easy extensions and modifications. The interpretation and discussion about advantages and differences of different methods will be ease as it covers transparent calculation procedures for the inventory and impact assessment. The source code is completely open all the times for developers who are willing to improve it.</td>
</tr>
<tr>
<td><strong>SimaPro</strong></td>
<td>SimaPro is one of the two most globally used LCA software tools developed by PRé Consultants. It is a full-service LCA tool and licenses must be purchased in order to download the software. The license is expensive and needed renewal from year to year. SimaPro is a professional tool to collect, analyze and monitor the environmental performance of products and services. User can easily model and analyze complex life cycles in a systematic and transparent way.</td>
</tr>
<tr>
<td><strong>TEAM-Tools for Environmental Analysis and Management</strong></td>
<td>TEAM is a tool developed by Pricewaterhouse Coopers Ecobilan Group for conducting life cycle environmental and cost profiles of products and technologies. It contains comprehensive database of over 600 modules with worldwide coverage.</td>
</tr>
<tr>
<td><strong>Umberto</strong></td>
<td>Umberto is developed by Institute for Environmental Informatics. Its main function is to visualize material and energy flow systems. Data can be modeled and calculated or taken directly from external information systems.</td>
</tr>
</tbody>
</table>
A LCIA methodology is a method used in determining the potential impacts. Different methodologies are using different approaches but all ultimately give the potential impacts associated to the study. Multiple impact assessment methods can be distinguished by midpoint and endpoint, referring to different stages in the cause-effect chain when calculating the result of LCA. Table 3.2 showed overview of some common methods in LCIA.

Table 2.11: Overview of common LCIA methodology (Karim, 2011)

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Impact Categories</th>
<th>Area of Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>E199</td>
<td>Endpoint-oriented: Acidification, carcinogenic, climate change, eco-toxicity, eutrophication, fossil resources, ionizing radiation, land-use, mineral resources, ozone layer depletion, and respiratory effects.</td>
<td>Ecosystem, resources, human health</td>
</tr>
<tr>
<td>Eco Scarcity</td>
<td>Endpoint-oriented: Air emissions, biodiversity losses, cancer caused by radio nuclides emitted to the sea, emissions to groundwater, emissions to soil, endocrine disruptors, gravel consumption, hazardous wastes (stored underground), landfilled municipal (reactive) wastes, ozone depletion, photochemical oxidant formation, primary energy resources, radioactive emissions, radioactive wastes, respiratory effects, surface water emissions, and water consumption.</td>
<td>Ecosystem, resources, human health</td>
</tr>
<tr>
<td>EDIP 2003</td>
<td>Midpoint-oriented: acidification, aquatic eutrophication, eco-toxicity, global warming, human toxicity, noise, ozone depletion, photochemical ozone formation, and terrestrial eutrophication.</td>
<td>Ecosystem, resources, human health</td>
</tr>
<tr>
<td>EPS 2000</td>
<td>Endpoint-oriented: Base cation capacity, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil), depletion of mineral reserves, fish and meat production capacity, life expectancy, morbidity, nuisance crop production capacity, production capacity for water, share of species extinction, severe morbidity and suffering, severe nuisance, and wood production capacity.</td>
<td>Abiotic stock resources, biodiversity, ecosystem production capacity, human health</td>
</tr>
<tr>
<td>IMPACT 2002+</td>
<td>Mixed: Acidification, aquatic eco-toxicity, aquatic eutrophication, damage to climate change, damage to ecosystem diversity, damage to human health, damage to resources, human toxicity, global warming, ionizing radiation, land occupation, non-renewable energy and mineral extraction, ozone depletion, photochemical oxidant formation, respiratory effects, terrestrial eco-toxicity, and terrestrial eutrophication.</td>
<td>Climate change, ecosystem quality, human health, resources</td>
</tr>
<tr>
<td>JEPIX</td>
<td>Endpoint-oriented: Air emissions, biodiversity losses, cancer caused by radio nuclides emitted to the sea, emissions to groundwater, emissions to soil, endocrine disruptors, gravel consumption, hazardous wastes (stored underground), landfilled municipal (reactive) wastes, ozone depletion, photochemical oxidant formation, primary energy resources, radioactive emissions, radioactive wastes, respiratory effects, surface water emissions, and water consumption.</td>
<td>Ecosystem, resources, human health</td>
</tr>
<tr>
<td>LIME</td>
<td>Mixed: Acidification, agricultural production, cataract, eco-toxic chemical, aquatic ecosystem, disaster causality, eutrophication, energy consumption, forestry production, fishery production, global warming, human-toxic chemical, hypo alimentation, infectious disease, land use, loss in land-use, ozone layer depletion, photochemical oxidant formation, regional air pollution, skin cancer, waste landfill, resource and consumption, respiratory disease, terrestrial ecosystem, thermal stress, and user cost.</td>
<td>Biodiversity, human health, net primary production, social welfare</td>
</tr>
<tr>
<td>LUCAS</td>
<td>Mixed: Abiotic resource depletion, acidification, aquatic eutrophication, climate change, eco-toxicity, human toxicity, land-use, ozone depletion, photochemical smog, respiratory effects, and terrestrial eutrophication.</td>
<td>Ecosystem, resources, human health</td>
</tr>
<tr>
<td>RECIPE</td>
<td>Mixed: Agricultural land occupation, climate change, damage to ecosystem diversity, damage to human health, damage to resources availability, freshwater eco-toxicity, freshwater eutrophication, fossil resource depletion, human toxicity, ionizing radiation, marine eco-toxicity, marine eutrophication, mineral resource depletion, natural land transformation, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial eco-toxicity, urban land occupation, and water depletion.</td>
<td>Ecosystem, resources, human health</td>
</tr>
<tr>
<td>TRACI</td>
<td>Midpoint-oriented: Acidification, eco-toxicity, eutrophication, fossil fuel depletion, global warming, human health cancer, human health non-cancer, human health criteria pollutants, ozone depletion, and smog formation</td>
<td>Ecosystem, resources, human health</td>
</tr>
</tbody>
</table>
LCA is a useful tool to quantify the environmental impacts of products or services from cradle-to-grave. LCA is able to assess multiple environmental impacts of a product or service systematically. LCA can play a role like carbon footprinting and other GHG accounting approaches in determining GHG emissions. Although some studies only include GHG emissions, LCA is also useful in evaluating other environmental performance. Conducting a LCA may able to provide more information especially in term of human health and environmental impact to the decision-makers. LCA results which present the environmental performance of a product or system can become one of a factor other than cost, technical performance and social acceptance when choosing alternatives. ‘Hotspot’ in a system can also be detected using LCA methodology to identify the process that creates the greatest impact to the environment. To compare the alternatives, the system boundary and functional unit chosen for study shall be same. Different scenarios also can be created using LCA software for modelling. Uncertainty analysis can be done in LCA for understanding correlations between input variables to output results to enhance significance of the generated results.

For instance, a study conducted by Mirjam et al. (2015) in United Kingdom showed that GHG emissions for generating electricity from forest residue and sawmill residue pellets was 132 g CO\textsubscript{2}eq/kWh and 140 g CO\textsubscript{2}eq/kWh respectively. This study was conducted by using SimaPro software with Ecoinvent database and CML 2001 impact assessment method. In Malaysia, rice husk and rice straw were burnt in the biomass–fired power plant for electricity generation would emit 217 g CO\textsubscript{2}eq/kWh and 430 g CO\textsubscript{2}eq/kWh of GHG respectively. The study was done by Shafie (2015) using openLCA software, utilizing international databank such as Australian Database, United
State Inventory Database and database in SimaPro software with CML 2001 impact assessment method.

A study had been done by Lausselet et al. (2016) to assess the environmental performance of a WtE plant located in central Norway which utilized local waste mix; waste mix with insertion of 10% car fluff, 5% clinical waste and 10% wood; as well as waste mix with insertion of 50% wood waste. The functional unit chosen was 1 kg of waste. Based on the results, there was a total contribution to potential impacts of climate change ranged from 265-637 g CO$_2$eq/kg of waste analyzed by Arda software with ReCiPe impact assessment method.

Based on the study done by Yay (2015), five scenarios for MSW management were created to make comparison using SimaPro software with CML-IA impact assessment method in Sakarya. Scenario 1 was MSW disposal with landfilling; Scenario 2 was landfilling with material recovery facility; Scenario 3 was landfilling with material recovery facility and composting; Scenario 4 was landfilling with incineration; and Scenario 5 was landfilling, material recovery facility, composting with incineration. The functional unit chosen was 1 ton of MSW. All the facilities were assumed to be placed at the same site. According to the LCA results of this study, the highest GHG emissions were generated by Scenario 1 with 1840 kg CO$_2$eq/ton while Scenario 5 contributed the lowest global warming potential impact (GWP 100a) which was -1030 kg CO$_2$eq/ton of MSW treated. From the environmental perspective, alternative 5 was the best MSW management system.

A study was conducted by Kommalapati et al. (2018) to study the environmental impact of a coal power plant with biomass co-firing in USA using LCA methodology. Four cases were being considered for this study which were utilization of 100% of coal; 5% biomass with 95% coal; 10% biomass with 90% coal; and 15% biomass with 85%
coal for the power plant. The LCA was conducted using SimaPro software with IMPACT 2002+ impact assessment method. The functional unit chosen was 1 kWh of electricity generated. 14 impact categories were included in IMPACT 2002+. The GHG emissions for the power plant were 1030 g CO$_2$eq/kWh for 100% of coal; 998 g CO$_2$eq/kWh for 5% biomass with 95% coal; 946 g CO$_2$eq/kWh for 10% biomass with 90% coal; and 893 g CO$_2$eq/kWh for 15% biomass with 85% coal. Transportation of the biomass (forest residue) had been identified for generating the greatest impact to environment due to the emissions from diesel used in trucks. Besides, analysis of 15% uncertainty had been carried out by varying transportation distance for 10% biomass with 90% coal; and 15% biomass with 85% coal cases suggested that there were four impact categories were greatly affected.

Previous LCA study had been done by Ramos et al. (2018) to evaluate environmental performance for solid waste management system in Portugal using GaBi software which involved baseline scenario with usage of landfill and WtE plant. Functional unit chosen was 1 ton of waste. 9 impact categories were involved under CML 2001 impact assessment method. The result showed a value of -170.9 kg CO$_2$eq for global warming potential (100 years) impact category. The result was then compared to a scenario for waste incineration and a scenario for landfilling in Europe which showed combined usage of landfill and WtE plant in a solid waste management system was a more sustainable option. After that, sensitivity analysis was conducted with 4 scenarios where Scenario 1 included construction of plant and transportation of waste; Scenario 2 included construction of plant and wastewater treatment facility; Scenario 3 involved a typical landfill with landfill gas collection system; and Scenario 4 involved waste incineration without electricity generation. The analysis was able to show which processes could affect the outcome significantly.
CHAPTER 3

METHODOLOGY

3.1 Case Study: Energy Recovery from Wood Waste

The study was done on an energy recovery facility which utilizes waste biomass to generate electricity. It is a 7MW biomass-fired power plant owned by a paper mill at Rasa, Selangor, Malaysia. This plant was the only WtE plant which utilized wood waste from industrial, commercial and institution as fuel that enrolled in FiT mechanism introduced by Malaysia government under biomass-solid waste category as of December, 2017.

Site visits had been made on March, 2017 and November, 2017 in order to collect relevant data. There were interview sessions with the plant engineer and operator to obtain data for the operation of biomass-fired plant.

Figure 3.1: Photos taken during site visit
3.2 Data Collection

Input data such as wood waste, amount of electricity, water and fuel needed to run daily operation of the plant had been obtained. Apart from the above data, the output data such as residue and amount of electricity supplied to national grid had been collected for the purpose of study. The material flows for energy recovery process from wood waste were shown in Figure 3.2.

![Material flows for biomass-fired power plant](image)

Figure 3.2: Material flows for biomass-fired power plant

However, there was some data that was unobtainable. Hence, secondary data of case studies from Ecoinvent database version 3.4 were used as references.

3.3 LCA Methodology

LCA is chosen as the methodology to carry out this study. LCA is applied to evaluate environmental impacts of wood waste to energy plant in generating electricity. LCA is a systematic set of procedures developed to compile, examine and evaluate the relevant flows of material and energy associated with the system; by translating those inventories (inputs and outputs) into environmental impacts that are directly attributable to the operation of a product or service system throughout its entire life cycle (Onn and Yusoff, 2010).
There are four stages in LCA: i) goal and scope definition, ii) life cycle inventory, iii) impact assessment, and iv) interpretation. Firstly, the goal and scope of the study should be defined. Besides, system boundaries must be clearly stated. After the goal and scope are defined, the inventory analysis can be started where all data of the processes are gathered. A life cycle inventory (LCI) is established as the data is presented in a report. However, the data from the inventory analysis will be further processed in the impact assessment where the different data is sorted into different categories. The total environmental impact of the studied system can be clearly evaluated through the impact assessment. Lastly, the LCA’s result is interpreted to evaluate, check and present the information so that the most significant environmental impact category and the life cycle stage can be identified.

Among available LCA software, SimaPro Analyst version 8.5 was used to perform this study. The software was running under Window 7 with 32-bit operating system for this study. SimaPro is one of the most common LCA tools being used worldwide. It is a full-service LCA software program provided by PRé Sustainability. Complex product systems can be modelled easily through SimaPro. LCI data at all stages of the model and results can also be easily assessed. This transparency is very useful in analyzing complex products and processes. SimaPro is able to calculate environmental impact of a system or service with its customizable parameters and Monte Carlo analytical capabilities to generate results with statistical accuracy. All the results can be easily traced back to their origin. Hence, users are able to identify data responsible, inventory stage, find errors and understand the “hotspots” in value chain.
3.4 **Goal and Scope Definition**

The goal of this study is to identify the potential of implementing WtE technology in Malaysia. The objectives of the study are to develop a LCA model for biomass-fired power plant to investigate all processes involved and evaluate the environmental impacts of the plant in generating electricity then compare with current national grid from the perspective of environmental impacts especially for GHG emissions.

3.5 **Functional Unit**

Functional unit reflects the function of the investigated product. In this case study, wood waste acts as a kind of biofuel to generate electrical energy. The focus is given to the potential of electricity generation by the biomass-fired power plant. Thus, the chosen functional unit for this LCA study is 1kWh of electricity generated by the plant.

3.6 **System Boundary**

The boundaries of wood waste-to-energy system incorporated the incoming of wood waste until its final discharge. Only inputs and outputs relative to the operation were included. Construction and maintenance of the plant were neglected. The system boundary for this LCA study was shown in the schematic diagram in Figure 3.3.
3.7 Limitation and Assumption

For this LCA model, transportation will only involve the transfer and loading of the wood waste during the operation. Transport distance and route during the collection of the wood waste and final disposal of clinker to landfill are neglected. There is no additional fuel is added for the combustion of wood waste in boiler as the plant is operating continuously since the first ignition. The wood waste consists of all kind of wooden furniture from household, branches, stumps, timbers, whole trees from street or park maintenance, wood pallets, wood chips and sawdust. The wood waste that was being fed into the boiler has a moisture content of less than 25%.

3.8 Impact Assessment Method

A LCIA methodology is a method which used in determining the potential impacts. There are many different impact assessment methods that included in SimaPro such as ReCiPe, ILCD 2011, USEtox, IPCC 2007, EPD (2013), Impact 2002+, CML-IA,
Traci 2.1, BEES+, Ecological Footprint, EDIP 2003, Ecological scarcity 2013, EPS 2000 & Greenhouse Gas Protocol and others. Different methodologies are using different approaches but all ultimately give the potential impacts associated to the study. Multiple impact assessment methods can be distinguished by midpoint and endpoint, referring to different stages in the cause-effect chain when calculating the result of LCA.

Among available LCIA methods, selection had been made where ReCiPe method was chosen to determine the environmental impacts for the wood waste to energy plant. ReCiPe is the most recent and harmonized indicator approach available in life cycle impact assessment developed together by CML, RIVM, Radboud University Nijmegen (RUN) and PRé Consultants. The main objective of ReCiPe method is to convert the long list of LCI results into a limited number of indicator scores which represent relative severity on the environmental impact categories (PRé Consultants, 2016). There are two levels of indicators for ReCiPe which can be seen as a fusion of CML and Eco-indicator where each covers three cultural perspectives. These perspectives include: i) individualist (I) based on short-term interest, effective for optimism future technology development to avoid arising problems, ii) hierarchist (H) considered the medium time frame, is the most common policy principles, also act as the default model, and iii) egalitarian (E) considered the longest time-frame, is a long term based precautionary principle thinking (PRé Consultants, 2016).

ReCiPe was chosen as the impact assessment method because it contains the broadest set of midpoint impact categories. It has 18 midpoint indicators. It utilizes environmental mechanism as the basis for modelling and uses impact mechanisms with global scope. ReCiPe is different from other methods where it includes the potential impacts from future extractions in inventory analysis, excluding such impacts in impact
assessment (PRé Consultants, 2016). Figure 3.4 presented categories and indicators at the midpoint and endpoint levels of ReCiPe method.

![Figure 3.4: Categories and indicators at midpoint and endpoint levels of ReCiPe method (PRé Consultants, 2016)](image)

The result of this study was presented at midpoint level as it considered more impact categories than endpoint level. Impact categories of midpoint level were environment-based. Hence, it was easier to interpret and discuss the results in term of environmental impacts instead of endpoint indicators that covered issues such as human health, ecosystem quality and resource depletion without indicating the source. The midpoint indicators were chosen because the midpoint results had lower statistical uncertainty. The midpoint impact categories included agricultural land occupation, climate change, freshwater eco-toxicity, freshwater eutrophication, fossil resource depletion, human toxicity, ionizing radiation, marine eco-toxicity, marine eutrophication, mineral resource depletion, natural land transformation, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial eco-toxicity, urban land occupation, and water depletion.
CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Life Cycle Inventory

Environmental performance of each life cycle process was evaluated by identifying inputs and outputs for every process. The inventory data was collected, calculated and then related to the functional unit for the calculation of the energy and material flows linked to each life cycle process and passed the system boundary. The processes of selected WtE for this LCA study are described. The involved and selected inventories from database will be listed out in this section.

4.1.1 General process flow

The WtE selected for this study was a biomass-fired power plant with capacity of 7MW which utilize recycled wood waste as fuel for generating electricity and heat. The process started after the wood waste was collected and reached the site.

![Figure 4.1: General process flow diagram](image)

Figure 4.1: General process flow diagram
a) Storage

The wood waste was stored at a dry, cool place. Segregation will be done manually to pick out the non-wooden waste.

b) Loading

The transportation only involved loading of the wood waste on site by excavator and wheel-loader. There are 2 excavators and 1 wheel-loader in use.

c) Chipping

The wood waste was sent to the chipper to cut into smaller pieces until become wood chips. There were two electric chippers in use.

d) Conveyer

Wood chips were sent into the boiler through conveyer belt.

e) Boiler

The waste wood chips being feed in approximately at 11.67ton/hr were burnt and produced heat. Water is being heated in the boiler to high temperature under pressure 45barG to produce with steam evaporation rate at 45ton/hr. Treated feed water passed through the economizer with plain and fined tubes to pick up heat from flue gas arising from combustion of the wood waste to raise temperature of the feed water. The flue gas then passed through air preheater to further recover heat for increasing thermal efficiency of boiler before passing dust collector and ESP. The residue of wood waste after burning will be removed out by submerged conveyer as bottom ash and clinker.

f) ESP

When flue gas passed the electrostatic precipitator, a high voltage electric field was created between discharged electrodes and collecting electrodes to ionize the gas. Electrostatic force propelled the charged dust particles onto collecting plates and formed...
dust layer. Treated gas flowed through outlet baffle and released to atmosphere through chimney. The dust layer would be dislodged by periodic rapping and discharged through dust hopper as fly ash.

g) Turbine and generator
Water is pressurized in a steam boiler and then superheated. The expanded steam flowed to a steam turbine which was connected to generator where conversion of thermal into energy to mechanical energy takes place to produce electricity to sustain the operation of power plant and sell back to grid. The exhausted steam was sent to low pressure distributor before supplying into industrial process. Part of the expanded exhausted steam would pass through surface condenser and the condensed water would send to deaerator so that dissolved gases could be removed before recycling the water back into economizer.

h) Residue of the burning wood waste (ash and clinker) and the dust from ESP is sent to landfill and ashes can be used for landfarming activities.

4.2 Inventories Selection

Table 4.1 showed the data collected for relevant processes and adjusted to functional unit. Table 4.2 showed the inventories selected for generation of 1kWh electricity fed into national grid by wood WtE plant. The inventory selection was made based on Ecoinvent database version 3.4 in SimaPro that exactly or partially matched the collected data at the studied plant. Air emissions data for loading process were extracted from previous LCA study done by Silvio (2017) on biomass loading using hydraulic loader in agriculture field while air emissions data for operation of biomass-fired power plant were extracted from previous LCA study done by Karin (2017) on heat and power cogeneration using wood chip.
Table 4.1: Collected inventory data

<table>
<thead>
<tr>
<th>Process</th>
<th>Material</th>
<th>Inventory Selection</th>
<th>Unit</th>
<th>Amount</th>
<th>Amount adjusted to functional unit (1 kWh)</th>
</tr>
</thead>
</table>
| **Loading**           | Wood waste                                    | Waste wood, post-consumer [GLO] waste wood, post-consumer, Recycled Content cut-off | kg/day | 280000  | 280000 kg  
|                       |                                               | [Cut-off, U]                                                                         |        |         | $6000 \text{ kW} \times 24 \text{ h} = 1.94 \text{ kg}$ |
|                       |                                               |                                                                                    |        |         | 1.94 kg of wood waste generated 1 kWh electricity |
|                       | Excavator                                     | Tractor, 4-wheel, agricultural [GLO] market for | APOS, U | -       | 2                                      |
|                       | Wheel loader                                  |                                                                                     |        |         | 1                                      |
|                       | Diesel                                        | Diesel [GLO] market group for | APOS, U | L/day   | 180                                     |
|                       |                                               | 180 L $\times \frac{1.94 \text{ kg}}{280000 \text{ kg}} = 0.00104 \text{ kg}$       |        |         | 0.832 kg/L is density of diesel.        |
| **Chipping**          | Electric chipper                              | Chipper, stationary, electric [GLO] market for | APOS, U | -       | 1                                      |
| **Conveying**         | Conveyor                                      |                                                                                     |        |         | 2                                      |
| **Biomass-fired**     | Electricity generation                        | MW/day                                                                              | 7      |         |                                        |
| **power plant**       | Electricity consumption                       | MW/day                                                                              | 1      |         |                                        |
|                       | Electricity fed into national grid            | MW/day                                                                              | 6      |         | electricity generation – self-consumption = electricity fed into national grid  \[7 \text{ MW} \div 1 \text{ MW} = 6 \text{ MW}\] |
|                       | Electrostatic precipitator                    | Dust collector, electrostatic precipitator, for industrial use [GLO] market for | -      | 1       |                                        |
|                       | Boiler                                        | Furnace, wood chips, with silo, 5000kW [GLO] market for | APOS, U | -       | 1                                      |
|                       | Ash and clinker                               | Inert waste, for final disposal [RoW] market for | inert waste, for final disposal | APOS, U | kg  | 28000                                     |
|                       |                                               |                                                                                     |        |         | $28000 \times \frac{1.94 \text{ kg}}{280000 \text{ kg}} = 0.194 \text{ kg}$ |
|                       | Water consumption                             | Water, decarbonised, at user [GLO] market for | APOS, U | ton     | 10                                      |
|                       |                                               |                                                                                     |        |         | $10000 \text{ kg} \times \frac{1.94 \text{ kg}}{280000 \text{ kg}} = 0.069286 \text{ kg}$ |
Table 4.2: Inventories for generation of 1kWh electricity fed into national grid by wood WtE plant

<table>
<thead>
<tr>
<th>Input</th>
<th>Unit</th>
<th>Amount</th>
<th>Output</th>
<th>Unit</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input from technosphere: materials/fuels</td>
<td></td>
<td></td>
<td>Emissions to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel [GLO] market group for APOS, U</td>
<td>kg</td>
<td>0.0020176</td>
<td>Carbon monoxide, fossil</td>
<td>kg</td>
<td>6.1498E-06</td>
</tr>
<tr>
<td>Shed [GLO] market for APOS, U</td>
<td>m²</td>
<td>8.536E-07</td>
<td>Carbon dioxide, fossil</td>
<td>kg</td>
<td>0.003201</td>
</tr>
<tr>
<td>Tractor, 4-wheel, agricultural [GLO] market for APOS, U</td>
<td>kg</td>
<td>1.1407E-04</td>
<td>Dinitrogen monoxide</td>
<td>kg</td>
<td>1.23578E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Methane, fossil</td>
<td>kg</td>
<td>1.3289E-07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nitrogen oxides</td>
<td>kg</td>
<td>4.6754E-09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NMVOC, non-methane volatile organic compounds, unspecified origin</td>
<td>kg</td>
<td>3.0846E-06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PAH, polycyclic aromatic hydrocarbons</td>
<td>kg</td>
<td>3.395E-09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Particulates, &lt; 2.5 um</td>
<td>kg</td>
<td>4.365E-06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sulfur dioxide</td>
<td>kg</td>
<td>1.0379E-06</td>
</tr>
</tbody>
</table>

Wood loading within facility

<table>
<thead>
<tr>
<th>Input</th>
<th>Unit</th>
<th>Amount</th>
<th>Output</th>
<th>Unit</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input from technosphere: materials/fuels</td>
<td></td>
<td></td>
<td>Emissions to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chipper, stationary, electric [GLO] market for APOS, U</td>
<td>kg</td>
<td>1.04372E-07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubricating oil [GLO] market for APOS, U</td>
<td>kg</td>
<td>3.96924E-16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel, low-alloyed, hot rolled [GLO] market for APOS, U</td>
<td>kg</td>
<td>7.9152E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wood chipping

<table>
<thead>
<tr>
<th>Input</th>
<th>Unit</th>
<th>Amount</th>
<th>Output</th>
<th>Unit</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input from technosphere: materials/fuels</td>
<td></td>
<td></td>
<td>Emissions to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor belt [RER] production APOS, U</td>
<td>m</td>
<td>3.14E+09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor belt [RoW] production APOS, U</td>
<td>m</td>
<td>6.368E+09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubricating oil [GLO] market for APOS, U</td>
<td>kg</td>
<td>9.925E+14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Input from technosphere: materials/fuels

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Quantity</th>
<th>Emissions to air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste wood, post-consumer [GLO] waste wood, post-consumer, Recycled Content cut-off</td>
<td>kg</td>
<td>1.94</td>
<td>Benzene</td>
</tr>
<tr>
<td>Ammonia, liquid [RoW] market for</td>
<td>APOS, U</td>
<td>kg</td>
<td>2.999E-07</td>
</tr>
<tr>
<td>Chlorine, gaseous [RoW] market for</td>
<td>APOS, U</td>
<td>kg</td>
<td>2.89E-05</td>
</tr>
<tr>
<td>Dust collector, electrostatic precipitator, for industrial use [GLO] market for</td>
<td>APOS, U</td>
<td>p</td>
<td>1.90959E-08</td>
</tr>
<tr>
<td>Lubricating oil [GLO] market for</td>
<td>APOS, U</td>
<td>kg</td>
<td>0.00012</td>
</tr>
<tr>
<td>Furnace, wood chips, with silo, 5000kW [GLO] market for</td>
<td>APOS, U</td>
<td>p</td>
<td>1.90959E-08</td>
</tr>
<tr>
<td>Heat and power co-generation unit, organic Rankine cycle, 1000kW electrical [GLO] market for</td>
<td>APOS, U</td>
<td>p</td>
<td>1.90959E-08</td>
</tr>
<tr>
<td>Sodium chloride, powder [GLO] market for</td>
<td>APOS, U</td>
<td>kg</td>
<td>2.89E-05</td>
</tr>
<tr>
<td>Water, decarbonised, at user [GLO] market for</td>
<td>APOS, U</td>
<td>kg</td>
<td>0.069286</td>
</tr>
</tbody>
</table>

### Outputs to technosphere: waste treatment

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste mineral oil [RoW] market for waste mineral oil</td>
<td>APOS, U</td>
<td>kg</td>
</tr>
<tr>
<td>Wastewater, average [RoW] market for wastewater, average</td>
<td>APOS, U</td>
<td>m³</td>
</tr>
<tr>
<td>Inert waste, for final disposal [RoW] market for inert waste, for final disposal</td>
<td>APOS, U</td>
<td>kg</td>
</tr>
</tbody>
</table>
4.3 Life Cycle Impact Assessment of Wood WtE Plant

Operation of any plant will definitely generate impacts to the environment. Results obtained which referred to the environmental impacts will be calculated with reference of the functional unit which was 1kWh of output electricity generated by the wood WtE with ReCiPe Midpoint (H) V1.13 / World Recipe H method. The impact on environment arising from the operation of wood waste to energy plant was defined and divided to 18 impact categories. Table 4.3 showed the result of analysis by SimaPro of a wood WtE plant to generate 1kWh electricity.

Table 4.3: Impact assessment of wood WtE in generating 1kWh of electricity

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Wood WtE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>kg CO₂ eq</td>
<td>0.0319</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>1.65E-09</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq U235 eq</td>
<td>0.00313</td>
</tr>
<tr>
<td>Photochemical oxidant formation</td>
<td>kg NMVOC</td>
<td>3.55E-07</td>
</tr>
<tr>
<td>Particulate matter formation</td>
<td>kg PM₁₀ eq</td>
<td>0.000219</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.0217</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.00606</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO₂ eq</td>
<td>0.00215</td>
</tr>
<tr>
<td>Agricultural land occupation</td>
<td>m²a</td>
<td>3.98E-05</td>
</tr>
<tr>
<td>Urban land occupation</td>
<td>m²a</td>
<td>7.4E-05</td>
</tr>
<tr>
<td>Natural land transformation</td>
<td>m²</td>
<td>8.61E-06</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.000591</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>6.05E-05</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>9.78E-05</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.000312</td>
</tr>
<tr>
<td>Fossil depletion</td>
<td>kg oil eq</td>
<td>2.2E-05</td>
</tr>
<tr>
<td>Metal depletion</td>
<td>kg Fe eq</td>
<td>0.00021</td>
</tr>
<tr>
<td>Water depletion</td>
<td>m³</td>
<td>0.00311</td>
</tr>
</tbody>
</table>
For impacts to human health, generation of 1 kWh electricity by wood WtE plant contributed 31.9 g CO$_2$ eq to climate change, 1.65E$^{-06}$ g CFC-11 eq in term of ozone depletion, 3.55E$^{-04}$ g NMVOC of photochemical oxidant formation, 0.219 g PM$_{10}$ eq of particulate matter formation, 3.13 Bq U235 eq of ionizing radiation and 21.7 g 1,4-DB eq of human toxicity.

For impacts to ecosystem, generation of 1 kWh from wood WtE plant caused 2.15 g SO$_2$ eq impacts to terrestrial acidification, 0.0978 g P eq impacts to freshwater eutrophication, 0.0605 g N eq impacts to marine eutrophication, 6.06 g 1,4-DB eq impacts to terrestrial eco-toxicity, 0.312 g 1,4-DB eq of impacts to freshwater eco-toxicity, 0.591 g 1,4-DB eq of impacts to marine eco-toxicity, 3.98E$^{-05}$ m$^2$a of impacts to agricultural land, 7.4E$^{-05}$ m$^2$a of impacts to urban land and -8.61E$^{-06}$ m$^2$ of impacts to natural land transformation.

For impacts to resource availability, generation of 1 kWh from wood WtE plant caused fossil depletion, metal depletion and water depletion of 2.2E$^{-05}$ kg oil eq, 0.00021 kg Fe eq and 0.00311 m$^3$ respectively.

Figure 4.2 presented the network flow chart generated by SimaPro showing the significant processes that contributed to environmental load. The red bar inside a box indicated the environmental burden contributed by that particular process while the thickness of line represented total environmental burden flowed between the processes.
Figure 4.2: Network flow chart
The environmental impacts were scaled in the form of %. The major contributors of environmental impacts for electricity generation by wood waste were the loading process and operation of biomass-fired power plant. The environmental impacts generated during chipping and conveying processes were not significant. Loading of wood waste within the facility involved excavator and wheel loader which consumed diesel for operation. Diesel was produced from crude oil or petroleum. Most environmental impacts created by the wood WtE system came from the biomass-fired power plant. This was due to biomass-fired power plant involved different compartments such as boiler, ESP, distributor, turbine and generator. Besides, the disposal of final products from the combustion of wood waste which were clinker and ash (inert waste) contributed significant impacts to the environment.

4.3.1 Impact Assessment by Processes of Wood WtE

Figure 4.3 presented comparison LCA characterization for different processes in energy recovery from wood waste.
Figure 4.3: Graph of LCA characterization for different processes in wood WtE
Based on the LCA characterization of different processes in electricity generation of 1kWh, operation of biomass-fired power plant created the highest impact which accumulated for more than 80% in term of climate change, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity, agricultural land occupation, urban land occupation and metal depletion. Operation of biomass-fired power plant was identified as the hotspot in wood WtE system which contributed primarily to human health and ecosystem impacts. Loading of wood waste within facility contributed more than 75% in ozone depletion, ionizing radiation and fossil depletion impact categories. Consumption of diesel by the machineries to load the wood waste created great impact in fossil depletion. Pollutants formed during diesel fuel combustion were the key contributors to human health impacts. Conveying process did not cause much impacts to the environment compared to other processes in the wood WtE system. Chipping process produced about 10% of impacts in term of metal depletion for the wood WtE system because the blade of the chipper needed to be replaced. The wood WtE system was actually generated environmental benefit to the natural land transformation.
4.3.2 Sensitivity Analysis

Based on above analysis, operation of biomass-fired power plant to generate electricity would have the greatest effect to environment. Figure 4.4 presented comparison of impact assessment between the case study and a scenario of power generation using wood chips in Malaysia. The scenario used for comparison was ‘heat and power co-generation, wood chips, 6667 kW’ obtained from database Ecoinvent 3.4. This dataset was created by Karin Treyer from Paul Scherrer Institute in year 2017 which represented heat and electricity generation with wood chips in Switzerland was adjusted to fit for Malaysia scenario. Wood chips were burnt in a boiler under excess air conditions whereas electricity was generated with the Organic Rankine Cycle steam generator. Also, ESP was installed to reduce emission of pollutants which was similar to the studied plant.
Figure 4.4: Comparison result between base scenario and scenario of power generation using wood chips in Malaysia
The result was presented in a score scaled from -100% to 100%. Contribution of each impact category for both scenarios conventional grape growing impacts were set with relative to 100%. Scenario of power generation using wood chips generated greater environmental impact than energy recovery by wood waste for all impact categories except for terrestrial acidification, marine eutrophication, photochemical oxidant formation as well as particulate matter formation. The most significant difference between these two scenarios occurred in the impact categories of freshwater eutrophication, agricultural land occupation, urban land occupation and natural land transformation.

4.4 Impact Assessment of Wood WtE Plant vs National Grid

The environmental impacts of every kWh of electricity generated by the wood WtE plant will be compared to the environmental impacts of every kWh generated from national grid based on previous study by Onn et al. (2017). Onn et al. (2017) used SimaPro software to perform data analysis and environmental assessment of Malaysia’s electricity mix using the LCI data from Malaysia Life Cycle Inventory Database (MYLCID). Conversion was made by regenerating same input and output flows of the database into SimaPro’s inventory since LCI data from MYLCID were provided in the format of GaBi software and performed LCIA using hierarchical perspective of the midpoint level indicators from the ReCiPe characterization method. Table 4.4 displayed the generated result and compared to impacts in generating 1kWh of electricity by conventional power plant.
Table 4.4: Impact assessment of wood WtE plant vs current national grid in generating 1kWh electricity

<table>
<thead>
<tr>
<th>SimaPro 8.5.0.0</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>Wood WtE</td>
</tr>
<tr>
<td>Calculation:</td>
<td>Impact assessment</td>
</tr>
<tr>
<td>Results:</td>
<td>Analyse</td>
</tr>
<tr>
<td>Product:</td>
<td>Generation of 1kWh electricity by wood WtE</td>
</tr>
<tr>
<td>Method:</td>
<td>ReCiPe Midpoint (H) V1.13 / World Recipe H</td>
</tr>
<tr>
<td>Indicator:</td>
<td>Characterisation</td>
</tr>
<tr>
<td>Skip categories:</td>
<td>Never</td>
</tr>
<tr>
<td>Exclude infrastructure processes:</td>
<td>No</td>
</tr>
<tr>
<td>Exclude long-term emissions:</td>
<td>No</td>
</tr>
<tr>
<td>Sorted on item:</td>
<td>Impact category</td>
</tr>
<tr>
<td>Sort order:</td>
<td>Ascending</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Wood WtE</th>
<th>National Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>kg CO$_2$ eq</td>
<td>0.0319</td>
<td>0.820</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>1.65E-09</td>
<td>4.739E-11</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq U235 eq</td>
<td>0.00313</td>
<td>0.0001043</td>
</tr>
<tr>
<td>Photochemical oxidant formation</td>
<td>kg NMVOC</td>
<td>3.55E-07</td>
<td>0.003</td>
</tr>
<tr>
<td>Particulate matter formation</td>
<td>kg PM$_{10}$ eq</td>
<td>0.000219</td>
<td>0.002</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.0217</td>
<td>0.025</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.00606</td>
<td>1.262E-05</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO$_2$ eq</td>
<td>0.00215</td>
<td>0.004</td>
</tr>
<tr>
<td>Agricultural land occupation</td>
<td>m$^2$a</td>
<td>3.98E-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Urban land occupation</td>
<td>m$^2$a</td>
<td>7.4E-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Natural land transformation</td>
<td>m$^2$</td>
<td>-8.61E-06</td>
<td>0.000</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.000591</td>
<td>0.0001968</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>6.05E-05</td>
<td>0.00011</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>9.78E-05</td>
<td>5.385E-07</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DB eq</td>
<td>0.000312</td>
<td>7.657E-06</td>
</tr>
<tr>
<td>Fossil depletion</td>
<td>kg oil eq</td>
<td>2.2E-05</td>
<td>9.569</td>
</tr>
<tr>
<td>Metal depletion</td>
<td>kg Fe eq</td>
<td>0.00021</td>
<td>0.225</td>
</tr>
<tr>
<td>Water depletion</td>
<td>m$^3$</td>
<td>0.00311</td>
<td>0.014</td>
</tr>
</tbody>
</table>

The environmental impacts of every kWh of electricity generated by the wood WtE plant will be compared to the environmental impacts of every kWh generated from national grid based on previous study by Onn et al. (2017). A total contribution of 31.9 g CO$_2$ eq GHG emissions (96.1% lower) was generated by the wood WtE plant whereas 820 g CO$_2$ eq was emitted by the national grid for every kWh of electricity generated. The wood WtE plant would produce more impacts to human health than current national grid for every kWh of electricity generation in term of ozone depletion (33.82%) and ionizing radiation (29.01%). However, the wood WtE plant generated slightly lower impacts in term of human toxicity (13.2%), photochemical oxidant
formation (99.99%) and particulate matter formation (89.05%) than current national grid in generating 1kWh of electricity.

Generation of 1kWh electricity from both wood WtE plant and national grid resulted in low impacts to ecosystem. Current national grid had zero impact on agricultural land occupation, urban land occupation and natural land transformation. The wood WtE plant would produce impacts of 3.98E-05 m²a, 7.4E-05 m²a and -8.61E-06 m² respectively in term of agricultural land occupation, urban land occupation and natural land transformation impacts. Impacts to terrestrial acidification (46.25%) and marine eutrophication (45%) generated by wood WtE plant were lower than national grid, whereas impacts to terrestrial eco-toxicity (47919%), marine eco-toxicity (200.3%), freshwater eco-toxicity (3974.70%) and freshwater eutrophication (18061.56%) generated by wood WtE plant were higher than national grid.

Generation of 1kWh from wood WtE plant created lesser impacts to resource availability than national grid. National grid produced huge impact to fossil depletion which was 9.569 kg oil eq (100%) higher compared to wood WtE plant with only 2.2E-05 kg oil eq due to electricity generation in Malaysia was dominated by fossil fuels such as natural gas, coal and oil. Generation of 1kWh electricity by national grid contributed 99.91% higher in term of metal depletion and 77.79% higher to water depletion than wood WtE plant.

4.5 Potential of WtE to Reduce Impact from Landfill

11th Malaysia Plan states that all types of waste will be managed in a holistic manner. The ultimate goal is to phase out the conventional landfilling. There have been various regulatory measures and policies to turn waste into a source of wealth through waste recovery for material extraction and conversion of waste to energy (Ministry of Energy, Green Technology and Water, 2017). 51% of solid waste generated by
Malaysian households is comprised of biodegradable waste, including food waste, garden waste, wood and husk. Decomposition of the biodegradable waste produces great volumes of methane. 90.9% of the methane gas emission in Malaysia is generated from landfills where methane contributes to 23% of the total GHG emissions in Malaysia (Ministry of Energy, Green Technology and Water, 2017).

The use of WtE technology is able to reduce the amount of solid waste being disposed to landfills. Malaysians generates approximately 33,000 tonnes of solid waste daily where 1.4% is comprised of wood waste (National Solid Waste Management Department, 2013). There is about 462 tonnes of wood waste generated per day being sent to landfills. If wood waste in Malaysia is used for energy recovery to be incinerated in biomass-fired power plant, there will be at least 168,630 tonnes of solid waste is diverted from landfills annually which eventually lead to reducing of the need for landfill space.

According to Morris (2008), burying 1 kg of wood waste in a landfill without landfill gas capture resulted in a net increase in GHG emissions of 0.374 kg CO₂ eq. WtE incineration for 1 kg of wood waste in the biomass-fired power plant generated GHG emissions of 0.0319 kg CO₂ eq. Disposal of wood waste to the landfill without energy recovery generates greater impact than WtE incineration in term of climate change. WtE incineration of 1 kg of wood waste can avoid 91.5% of GHG emissions compared to dispose the wood waste into a landfill without energy recovery. The GHG emissions value for WtE incineration and landfilling of other types of waste may not as low as wood waste since biogenic CO₂ emissions were considered for biomass. If wood waste in Malaysia is incinerated in biomass-fired power plant instead of landfiling, there will be approximately 158.05 tonnes CO₂ eq of GHG emissions avoidance daily and 57,688.32 tonnes CO₂ eq of GHG emissions annually.
4.6 Potential of WtE as Renewable Energy

In Malaysia, there is about 462 tonnes of wood waste generated per day being sent to landfills. 462 tonnes of wood waste can generate about 237,600 kWh of electricity daily and 86,724.2 MWh annually. If the biomass-fired power plant which utilized wood waste as fuel is included in electricity mix, there will be an avoidance of 187,252.56 kg CO\textsubscript{2} eq GHG emissions daily and 68,347.34 tonnes CO\textsubscript{2} eq GHG emissions annually in term of electricity generation as the current electricity generation for Malaysia is emitting 820 g CO\textsubscript{2} eq of GHG emissions for every kWh.

Government of Malaysia had been promoting RE resources such as biogas, biomass, hydro and solar since the 8th Malaysia Plan (2001–2005). RE was added to national electricity mix due to the rising of global issue on climate change. Table 4.5 stated the target of cumulative total RE in National Renewable Energy Policy 2010.

Table 4.5: Malaysia’s cumulative total RE target (Ministry of Energy, Green Technology and Water (2011)).

<table>
<thead>
<tr>
<th>Year</th>
<th>Targeted cumulative total RE (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biogas</td>
</tr>
<tr>
<td>2017</td>
<td>155</td>
</tr>
<tr>
<td>2020</td>
<td>240</td>
</tr>
<tr>
<td>2030</td>
<td>410</td>
</tr>
</tbody>
</table>

Since Malaysia had pledged to cut the country’s GHG emissions intensity based on the GDP by up to 45% by 2030 relative to 2005 value, where 35% on an unconditional basis with a further 10% condition upon climate finance, technology transfer and capacity building during the 21\textsuperscript{st} United Nations Framework Convention on Climate Change (UNFCCC), massive transformation should be taken to develop the national grid towards greener sources (Onn et al., 2017; Malaysia Pledges to Cut CO\textsubscript{2} Emissions Intensity by 45% by 2030, 2017).
Malaysia’s government aimed to increase the share of RE progressively in national electricity mix for reduction of carbon emissions as the highest carbon emissions was contributed by energy sector. However, the targeted cumulative total RE was not achieved due to output intermittency, location and system constraints, as well as technology development in Malaysia. In year 2017, the total cumulative RE installed capacity was far from the target and only achieved about 35% of it. Based on the target set by Minister of Energy, Green Technology and Water, cumulative total RE should achieved 1440 MW where 10.76% of RE was contributed by biogas, 34.72% by biomass, 19.44% by solid waste, 27.78% by small hydro and 7.3% by solar PV. As of December, 2017, there was only 514.44 MW of cumulative total RE. The largest share was contributed by solar PV which at 66.8% of the cumulative total RE. 15.7% was from biomass while 10.2% of current RE was from biogas. 5.9% of RE was from mini hydro. There was only 1.4% of cumulative total RE contributed by solid waste which utilized waste wood for electricity generation.

31.9 g CO\(_2\) eq of GHG emissions was emitted for every kWh of electricity generated by the wood WtE plant. Based on work done by Intergovernmental Panel on Climate Change (2014), carbon dioxide equivalent (CO\(_2\) eq) findings on biogenic CO\(_2\) emissions and albedo effect of biomass power plant was 27 g CO\(_2\) eq/kWh. This value did not consider the emissions of infrastructure and supply chains. While, biomass power plant emitted 10-101 g CO\(_2\) eq GHG emissions for every kWh of electricity generation as reported by World Nuclear Association (2010). The life cycle greenhouse gas emissions for biomass electricity generator were varied from 14 to 35 g CO\(_2\) eq/kWh as reported by Sovacool (2008). The percentage of GHG emissions from WtE was 96.1% lower than the GHG emission generated from the electricity generation mix of current national grid as more than 90% of the electricity generation mix Malaysia was composed of fossil fuels. Electricity mix Malaysia was dominant by 41% of coal
and 46.3% of natural gas. Hydropower contributed 10.7% in generation mix at the end of year 2015 (Energy Commission, 2016). Coal power plant emitted an average of 820 g CO\textsubscript{2} eq while gas power plant emitted 490 g CO\textsubscript{2} eq of GHG emissions for 1kWh electricity generation (IPCC Working Group III, 2014). The value for GHG emissions was much lower for wood WtE plant because biogenic CO\textsubscript{2} emissions were considered in this case study. Biogenic and fossil CO\textsubscript{2} emissions were not equated in this case as combustion of wood waste did not increase the amount of carbon in global carbon cycle.

WtE could be the potential source for RE generation as it produced low GHG emissions for every kWh of electricity generation. The latest target for Malaysia was to achieve 25% of RE in generation mix by year 2025. A scenario was created to show the relationship between the percentages of GHG emissions reduction that is in line with Malaysia's commitment to reduce GHG emissions. If Malaysia succeeded in achieving the target set by Sustainable Energy Development Authority by introducing WtE as potential RE source from biomass, there will be an avoidance of 914,196 tonnes CO\textsubscript{2} eq of GHG emissions annually at year 2020, and in year 2030, there will be an avoidance of 1,363,413 tonnes CO\textsubscript{2} eq of GHG emissions annually. These will ultimately help Malaysia in cutting the country’s GHG emissions intensity since the highest GHG emissions were contributed by the energy sector in Malaysia. Table 4.6 showed the potential of CO\textsubscript{2} avoidance in line with RE target set by SEDA Malaysia.

Table 4.6: Potential of CO\textsubscript{2} avoidance as RE target is achieved

<table>
<thead>
<tr>
<th>Year</th>
<th>WtE generation (GWh)</th>
<th>GHG emissions with current electricity mix (tonnes of CO\textsubscript{2} eq)</th>
<th>GHG emissions with WtE (tonnes of CO\textsubscript{2} eq)</th>
<th>GHG emissions avoidance with targeted RE capacity and WtE as potential source (tonnes of CO\textsubscript{2} eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>1160</td>
<td>951,200</td>
<td>37,004</td>
<td>914,196</td>
</tr>
<tr>
<td>2030</td>
<td>1730</td>
<td>1418,600</td>
<td>55,187</td>
<td>1,363,413</td>
</tr>
</tbody>
</table>
CHAPTER 5

CONCLUSION

5.1 Conclusion

Although WtE technologies are effective in solid waste management and electricity generation, installation of WtE plant in Malaysia, a developing country is still limited. LCA methodology was applied to assess a WtE plant which was the only one that currently involved in the FiT mechanism introduced by government under biomass-solid waste category from environmental perspective. The biomass-fired power plant which utilized wood waste as fuel produced only 31.9 g CO$_2$ eq in generating 1kWh of electricity. The GHG emissions of the plant were much lower than the national electivity grid which was dominated by fossil fuel-fired power plant. However, the biomass-fired power plant would produce more impacts to environment than national grid for every kWh of electricity generation in term of ozone depletion, ionizing radiation, terrestrial eco-toxicity, agricultural land occupation, urban land occupation, natural land transformation, marine eco-toxicity and freshwater eutrophication.

Government of Malaysia had been promoting use of RE where biomass and solid waste were included in generation of RE. Government aimed to achieve 1440 MW of cumulative total RE by year 2017 where 34.72% was contributed by biomass and 19.44% by solid waste but there was only 514.44 MW of cumulative total RE achieved at year 2017. There was only 1.4% of cumulative total RE contributed by solid waste which utilized waste wood for electricity generation and 15.7% from biomass. If Malaysia succeeded in achieving the RE target set by Sustainable Energy Development Authority, there could be an avoidance of 914,196 tonnes CO$_2$ eq of GHG emissions annually after year 2020 and 1,363,413 tonnes CO$_2$ eq of GHG emissions annually after
year 2030. The implementation of WtE technologies could be seen as a potential drive to reduce greenhouse gas emissions and act a source of RE towards green growth and sustainable development of Malaysia.

5.2 Summary based on Objectives

The first objective of this study is to create an environmental profile for selected Waste-to-Energy technology which is a biomass-fired power plant using life cycle assessment methodology. The second objective is to compare the environmental impacts of electricity generation from the biomass-fired power plant and current national grid. The third objective is to determine the potential of implementation of wood WtE in Malaysia based on the impact assessment modelling result for assessing renewable energy potential of the biomass (solid waste).

5.2.1 Environmental Profile of Wood WtE

LCA methodology was applied to assess a 7MW biomass-fired power plant at Rasa, Selangor from environmental perspective by using SimaPro software. This biomass-fired power plant was the only WtE plant that currently involved in the FiT mechanism introduced by government of Malaysia under biomass-solid waste category. An environmental profile was created for the wood WtE plant. LCI which involved quantification of environmentally-relevant flows of materials and energy required was established for the wood WtE plant in generating 1kWh of electricity. To analyze the wood WtE plant, selected method was ReCiPe Midpoint (H). The impacts on environment arising from the operation of wood waste-to-energy plant to generate 1kWh of electricity was defined and expressed in 18 impact categories including human toxicity, ionizing radiation, photochemical oxidant formation, ozone depletion, particulate matter formation, climate change, terrestrial eco-toxicity, marine eco-toxicity, freshwater eco-toxicity, agricultural land occupation, urban land occupation,
natural land transformation, terrestrial acidification, marine eutrophication, freshwater eutrophication, fossil depletion, metal depletion and water depletion.

For impacts to human health, generation of 1kWh electricity by wood WtE plant contributed 31.9 g CO$_2$ eq to climate change, 1.65E$^{-06}$ g CFC-11 eq in term of ozone depletion, 3.55E$^{-04}$ g NMVOC of photochemical oxidant formation, 0.219 g PM$_{10}$ eq of particulate matter formation, 3.13 Bq U235 eq of ionizing radiation and 21.7 g 1,4-DB eq of human toxicity. For impacts to ecosystem, generation of 1kWh from wood WtE plant caused 2.15 g SO$_2$ eq impacts to terrestrial acidification, 0.0978 g P eq impacts to freshwater eutrophication, 0.0605 g N eq impacts to marine eutrophication, 6.06 g 1,4-DB eq impacts to terrestrial eco-toxicity, 0.312 g 1,4-DB eq of impacts to freshwater eco-toxicity, 0.591 g 1,4-DB eq of impacts to marine eco-toxicity, 3.98E$^{-05}$ m$^2$a of impacts to agricultural land, 7.4E$^{-05}$ m$^2$a of impacts to urban land and -8.61E$^{-03}$ m$^2$ of impacts to natural land transformation. For impacts to resource availability, generation of 1kWh from wood WtE plant caused fossil depletion, metal depletion and water depletion of 2.2E$^{-05}$ kg oil eq, 0.00021 kg Fe eq and 0.00311 m$^3$ respectively.

5.2.2 Comparison of Wood WtE to National Grid

The biomass-fired power plant generated lesser impacts to environment than national grid for every kWh of electricity generation in term of climate change, particulate matter formation, photochemical oxidant formation, human toxicity, marine eutrophication, freshwater eco-toxicity, terrestrial acidification, fossil depletion, metal depletion and water depletion.

When analyzing the biomass-fired power plant which utilized waste wood as fuel, the main concern was given to climate change impact which evaluated GHG emissions of the wood WtE system. The GHG emissions of wood WtE was being
compared to national grid in electricity generation which were dominant by fossil fuels-fired power plants. The biomass-fired power plant emitted 31.9 g CO$_2$ eq in generating 1kWh of electricity. GHG emissions of the biomass-fired power plant were much lower than the electricity grid mix of Malaysia (820 g CO$_2$ eq).

5.2.3 Potential of Implementation of Wood WtE Technologies in Malaysia

There is about 462 tonnes of wood waste generated per day being sent to landfills. If all wood wastes in Malaysia are used for energy recovery to be incinerated in biomass-fired power plant, there will be 168,630 tonnes of solid waste is diverted from landfills. Disposal of wood waste to the landfill without energy recovery generates greater impact than WtE incineration in term of climate change. WtE incineration of 1 kg of wood waste can avoid 91.5% of GHG emissions. There will be approximately 158.05 tonnes CO$_2$ eq of GHG emissions avoidance daily and 57,688.32 tonnes CO$_2$ eq of GHG emissions annually if the wood waste in Malaysia is incinerated in the biomass-fired power plant instead of landfilling. 462 tonnes of wood waste can generate about 237,600 kWh of electricity daily and 86,724.2 MWh annually. If the biomass-fired power plant which utilized wood waste as fuel is included in electricity mix, there will be an avoidance of 187,252.56 kg CO$_2$ eq GHG emissions daily and 68,347.34 tonnes CO$_2$ eq GHG emissions annually in term of electricity generation.

WtE technologies emerged as an alternative for solid waste management in Malaysia since there has been massive increase in the quantity of waste generated. With WtE technologies, energy can be recovered from the waste to solve two problems simultaneously: treating waste as well as generating significant amount of energy to be included in electricity mix. Implementation of WtE technologies in Malaysia, a developing country is still limited especially for the treatment of MSW. Although the supply of combustible waste is stable with approximate waste generation of 33,000
tonnes daily, WtE incineration is not suitable for MSW with high moisture content and organic fraction. Malaysia has a lot of biomass and wood waste resources available for exploitation such as the by-products or residues from agricultural sector. These wastes are suitable for WtE technologies since wood has high net calorific value which is suitable for incineration.

5.3 Limitations

In conducting this study, there are several limitations. There is lack of data on LCA study of waste-to-energy in Malaysia since very few researches has been done in this field. The selected inventory inputs and outputs from database provided by SimaPro software are actually from case studies carried out in other countries, mostly developed countries. Selected inventories shall be similar to the primary data obtained for this study. Hence, there would be slight differences in the obtained result as some selected inventory data does not exactly match with the primary data and suit the trend of Malaysia, a developing country.

Moreover, some missing data could affect the reliability of the obtained results. The operation of a WtE plant involved many processes but not all inputs and outputs parameters for the processes got measured and recorded. When there was no data for the process, assumption would be made that no impact was cause by that particular process. The overall result might be affected if there was missing in data.

Nowadays, new processes and products are continually being introduced to the market. In order to ensure availability of updated data, having an ongoing data collection is necessary but it is a very time and cost consumed work. Thus, to get up-to-date information for LCA study is becoming more challenging.
5.4 Recommendations

The use of LCA in Malaysia is still limited since consumers, public and private sectors lack of awareness on the potential benefits of LCA. More LCA studies should be done in the fields of solid waste management and waste-to-energy technologies to help in setting up database that suit Malaysia’s scenario. The establishment of solid waste management database of Malaysia ensures that more reliable data could be obtained, thus more accurate result can be generated for the future study in Malaysia’s solid waste management sector.

In future, more comprehensive LCA studies and researches should be carried out related to waste-to-energy processes or technologies such as incineration, gasification, pyrolysis, anaerobic digestion and landfill gas recovery. Assessment and comparison can be made among these processes and technologies from different aspects including economic, environmental and social impacts to evaluate the potential WtE in Malaysia. Solid waste as a potential source of RE can also be determined. These may help the policy makers in making decision related to solid waste management, WtE technology or renewable energy policies.
REFERENCES


Gregory, L. R. (October, 2011). *Gaps in the implementation of environmental law at the national, regional and global level*. Paper presented at First Preparatory Meeting of the World Congress on Justice, Governance and Law for Environmental Sustainability, Kuala Lumpur, Malaysia.


LIST OF PUBLICATIONS AND PAPERS PRESENTED

Publications: