A LIFE CYCLE ASSESSMENT APPROACH FOR SUSTAINABLE RESIDENTIAL BUILDINGS IN MALAYSIA

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A LIFE CYCLE ASSESSMENT APPROACH FOR SUSTAINABLE RESIDENTIAL BUILDINGS IN MALAYSIA

ABSTRACT

The building industry has a significant impact on the environment due to massive natural resources and energy it uses throughout its life cycle. Life cycle assessment (LCA) method has been accepted internationally and has been used to quantify the environmental impact of processes and products including in the building industry. The objectives of this thesis are to evaluate and benchmark conventional residential buildings and an energy efficient building in Malaysia by using LCA. This thesis has also quantified a potential environmental impact reduction by adopting selected green building standard and finally estimate the carbon emission reduction. Three residential buildings in Malaysia with different specifications were selected as case studies namely a semi-detached government quarters (GQ), a semi-detached house by a private developer (PD), and an energy efficient house (EEH). The environmental impacts of the buildings were assessed by using SimaPro under the cradle-to-grave system boundaries over a fifty years period by using CML 2001 and Eco-indicator 99. The findings of this thesis state that the energy consumption and the building materials selection have the major influence on the environmental impact. The adoption of energy efficient building products, the installation of solar panel, and a reduction in the air-conditioning usage can lower the energy consumption of the building significantly and subsequently reduce the overall environmental impact. Based on the potential improvement, it is estimated that the selected residential building in Malaysia has the potential to reduce 6.28 Mt of CO_2 or 3.36% reduction in carbon emission intensity per GDP, in line with the pledge by the Prime Minister of Malaysia for 40% reduction by the year 2020. Therefore, the LCA approach to the residential building in Malaysia is crucial due to the ability to assess the

environmental impact based on the selection of materials and specification of the building for further improvement even before the building is being constructed.

Keywords: life cycle assessment; residential buildings; Malaysia; sustainable

PENDEKATAN PENILAIAN KITARAN HAYAT UNTUK BANGUNAN KEDIAMAN MAMPAN DI MALAYSIA

ABSTRAK

Industri pembinaan mempunyai kesan yang besar kepada alam sekitar kerana sumber semula jadi besar-besaran dan tenaga yang digunakan sepanjang kitaran hayatnya. Kaedah Penilaian Kitaran Hayat (LCA) telah diterima di peringkat antarabangsa dan telah digunakan untuk mengukur kesan alam sekitar daripada proses dan produk termasuk di dalam industri pembinaan. Objektif tesis ini adalah untuk menilai dan menanda aras bangunan kediaman biasa dan bangunan yang cekap tenaga di Malaysia dengan menggunakan kaedah LCA. Tesis ini juga telah menilai potensi pengurangan kesan alam sekitar dengan mengamalkan standard bangunan hijau terpilih dan akhirnya menganggarkan pengurangan pelepasan karbon. Tiga bangunan kediaman di Malaysia dengan spesifikasi yang berbeza telah dipilih sebagai kajian kes iaitu kuarters berkembar kerajaan (GQ), sebuah rumah berkembar oleh pemaju swasta (PD), dan rumah yang cekap tenaga (EEH). Kesan alam sekitar daripada bangunan-bangunan telah dinilai dengan menggunakan perisian SimaPro dengan sistem sempadan buaian-ke-kuburan (cradle-to-grave) untuk tempoh lima puluh tahun dengan menggunakan CML 2001 dan Eko-indikator 99 (Eco-indicator 99). Hasil penemuan tesis ini adalah penggunaan tenaga dan pemilihan bahan binaan mempunyai pengaruh yang besar ke atas kesan alam sekitar. Penggunaan produk bangunan cekap tenaga, pemasangan panel solar, dan pengurangan dalam penggunaan penghawa dingin boleh mengurangkan penggunaan tenaga bangunan itu dengan ketara dan seterusnya mengurangkan kesan alam sekitar secara keseluruhan. Berdasarkan potensi pengurangan ini, dianggarkan bahawa bangunan kediaman di Malaysia mempunyai potensi untuk mengurangkan 6.28 Mt CO_2 atau 3.36% pengurangan intensiti pelepasan karbon per KDNK, sejajar dengan yang dijanjikan oleh

Perdana Menteri Malaysia untuk mengurangkan 40% pada tahun 2020. Oleh yang demikian, pendekatan kaedah LCA ke bangunan kediaman di Malaysia adalah sangat penting atas keupayaan untuk menilai kesan alam sekitar berdasarkan pemilihan bahan dan spesifikasi pembinaan yang memerlukan penambahbaikan sebelum bangunan itu dibina.

Kata kunci: penilaian kitaran hayat; bangunan kediaman; Malaysia; mampan

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LIST OF ABBREVIATIONS

AAC	:	Aerated autoclaved concrete
ABC	:	Awareness & Building Capacity of Sustainable Energy Lifestyle among Urban Household
ACEM	:	Association of Consulting Engineers Malaysia
ASHRAE	:	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	:	American Society for Testing and Materials
BEES	:	Building for Environmental and Economic Sustainability
BEIT	:	Building Energy Intensity Tool
BREEAM	:	Building Research Establishment Environment Assessment Methodology
CAD	:	Computer aided design
CASBEE	:	Comprehensive Assessment System for Building Environmental Efficiency
CAST	:	Cawangan Alam Sekitar Dan Tenaga (Environment and Energy Department)
CDM	:	Clean development mechanism
CETDEM	:	Centre for Environment, Technology, and Development, Malaysia
CFC	:	chlorofluorocarbon
CIDB	:	Construction Industry Development Board Malaysia
CML	:	Centrum Milieukunde Leiden (Institute of Environmental Sciences Leiden University)
CO2	:	Carbon dioxide
CREAM	:	Construction Research Institute of Malaysia
DANIDA	:	Danish International Development Agency

DHW	:	Domestic hot water
DOE	:	Department of Environment
EDP	:	Environmental Product Declaration
EEH	:	Energy efficient house
EIO-LCA	:	Economic Input-Output Life Cycle Assessment
ELCD	:	European reference Life Cycle Database
EOL	:	End-of-life
EQ	:	Ecosystem quality
EQA	:	Environment Quality Act
FELDA	:	Federal Land Development Authority
FIT	:	Feed-in Tariff
GBI	:	Green Building Index
GDP	:	Gross domestic product
GEO	:	Green Energy Office
GFA	:	Gross floor area
GHG	:	Greenhouse gas
GQ	:	Government quarters
GTFS	:	Green Technology Financing Scheme
GUI	:	Graphical user interface
GWh	:	GigaWatt Hour
GWP	:	Global warming potential
HCFC	:	Hydrochlorofluorocarbon
HFC	:	Hydrofluorocarbons
HH	:	Human health
HK-BEAM	:	Hong Kong Building Environmental Assessment Method
HT	:	Human toxicity
HVAC	:	Heating, ventilation and cooling

IBS	:	Industrialised building system
ICF	:	Insulated concrete form
ISO	:	International Organization for Standardisation
JKR	:	Jabatan Kerja Raya (Public Works Department)
KDNK	:	Keluaran Negara Kasar
KeTTHA	:	Ministry of Energy, Green Technology and Water
kg 1,4-DCB eq.	:	Kilogram 1,4 dichlorobenzene equivalent
kg C_2H_6 eq	:	Kilogram ethane equivalent
kg CFC-11eq	:	Kilogram chlorofluorocarbon-11 equivalent
kg CO_2 eq	:	Kilogram carbon dixiode equivalent
kg Sb eq	:	Kilogram antimony equivalent
kg SO_2 eq	:	Kilogram sulphur dioxide equivalent
km	:	Kilometre
kWh	:	Kilowatt hour
kWh/m2	:	Kilowatt hour per square meter
kWp	:	Kilowatt-Peak
LCA	:	Life cycle assessment
LCI	:	Life cycle inventories
LCIA	:	Life cycle impact assessment
LEED	:	Leadership in Energy & Environmental Design
LEO	:	Low Energy Office
m^2	:	Meter square
m^2K/W	:	Metres squared Kelvin per Watt
MBIPV	:	Malaysia Building Integrated Photovoltaic
MDG	:	Millennium Development Goals

MEWC	:	Ministry of Energy, Water, and Communications
MIEEIP	:	Malaysian Industrial Energy Efficiency Improvement Project
MS	:	Malaysian Standard
Mt	:	Metric ton
MTHPI	:	National Green Technology and Climate Change Council
MYLCID	:	Malaysian Life Cycle Inventory Database
NAHB	:	National Association of Home Builders
NAPIC	:	National Property Information Centre
NIST	:	National Institute of Standards and Technology
NRE	:	Ministry of Natural Resources and Environment
NREL	:	National Renewable Energy Laboratory
ODP	:	ozone layer depletion
OTTV	:	overall thermal transfer value
PAM	:	Pertubuhan Akitek Malaysia
PD	:	Private Developer
pH	:	Penarafan Hijau
PTM	:	Pusat Tenaga Malaysia
PV	:	Photo-Voltaic
PVC	:	PolyVinyl Chloride
R	:	Resources
RNC	:	Residential New Construction
SDG	:	Sustainable Development Goals
SEDA	:	Sustainable Energy Development Authority
SETAC	:	Society of Environmental Toxicology and Chemistry
SIRIM	:	Standards and Industrial Research Institute of Malaysia
UN	:	United Nations
UNCED	:	UN Conference on Environment and Development

UNDP	:	United Nations Development Programme
UNEP-SBCI	:	United Nations Environment Programme's Sustainable Building & Climate Initiative
UNFCC	:	United Nations Framework Convention on Climate Change
W/m^2	:	Watts per square metre
W/m^2K	:	Watts per square metre Kelvin
WCPJ	:	Working with the Community on Energy Efficiency at Household Level in Petaling Jaya

CHAPTER 1 : INTRODUCTION

1.1 Introduction

Climate change and sustainable development are among major issues being discussed these days all over the world. These issues demand improvement in government policies and industry standard. The United Nations (UN) has played a key role in managing these concerns by initiating various environmental programs. Millennium Development Goals (MDGs) for example, has been set by the UN to improve the life of millions of people with eight major goals. One of its goals is to ensure environmental sustainability by pushing every country to incorporate principles of sustainable development into their policies and programs by the year 2015 (United Nations, 2011). The introduction of Kyoto Protocol in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC) was established to fight climate change. The protocol has bound 37 countries and European communities to take action on global warming and greenhouse gas emission by 2012 (United Nations Framework Convention on Climate Change, 2011).

Although Malaysia is not part of the Kyoto Protocol, the Malaysian Government has addressed the issues on climate change by the introduction of the National Policy on the Environment in 2002 and the National Policy on Climate Change in 2009 and National Green Technology Policy in 2009 under the Ministry of Energy, Green Technology and Water (KETTHA). These published policies serve as the framework for government agencies, industries and community to improve the environmental management and climate change for sustainable future (NRE, 2013). Moreover, the Prime Minister of Malaysia has pledged at the United Nations Climate Change Conference 2009 that Malaysia is adopting an indicator of a voluntary reduction of up to 40 percent in terms of emissions intensity of GDP (gross domestic product) by the year 2020 compared to

2005 levels (BERNAMA, 2009). The building industry has been identified as one of the key areas under the KeTTHA that needs major improvement on the overall processes.

The building industry contributes significantly to the economy and social development but is also responsible for a significant impact on the environment due to natural resource consumption and the emission released (Arena & de Rosa, 2003). The building industry is a combination of different industries from mining, manufacturing, construction to demolition. Each process will direct or indirectly contribute to solid wastes and harmful emissions. Researchers (Kofoworola & Gheewala, 2009; Utama & Gheewala, 2009) have identified that building operation consumes the largest energy (electricity) consumption. Saidur (2009) has also identified that the global energy consumption from residential and commercial buildings had increased gradually between 20% and 40% in developed countries.

Due to the increasing awareness of environmental issues, numerous studies on reduction of building's energy consumption and its environmental impact including the implementation of life cycle assessment (LCA) have been conducted (Singh, Berghorn, Joshi, & Syal, 2011). Currently, LCA method is one of the assessment tools being applied to assess the environmental impact thoroughly. It has been widely accepted as a tool to improve processes and services environmentally and can be utilised in a broader area such as in the building industry (Fava, Baer, & Cooper, 2009; Ortiz, Castells, & Sonnemann, 2009). LCA is a systematic analysis for quantifying industrial process and products, by itemising flows of energy and material use, wastes released to the environment, and evaluating alternatives for environmental improvements (Fay, Treloar, & Iyer-Raniga, 2000).

The first life cycle assessment (LCA) has been reportedly started in the 1960s and then modernise over the years which later developed into ISO standards in the late 1990's (Hunt, Franklin, & Hunt, 1993; Ove Arup & Partners Hong Kong Ltd, 2007). In Malaysia, the government has empowered Standards and Industrial Research Institute of Malaysia (SIRIM) under the Ninth Malaysian Plan to initiate the National LCA Project. The aims are to carry out LCA studies, support the National Eco-labelling programme and fulfill the international standards to reduce the environmental impact of products and services (LCA Malaysia, 2009). Numerous LCA research conducted in Malaysia were focused on the palm oil industry but has since broaden to other field such as waste, water treatment process, laundry detergent and alternative electricity generation.

At the moment, limited LCA research on buildings in Malaysia is available. The research are mainly focused on the impact assessment of different building materials. A few research studies concentrate on the advantages of incorporation of industrialised building system (IBS) to the conventional construction system. Fujita et al. (2008) used LCA to estimate CO_2 emission for concrete and timber based house by using input-output method during pre-use and operation phase. Omar et al. (2014) compared the pre-use phase of two-storey houses. The first house was constructed using conventional concrete house and the second house using an IBS system with precast wall panel using hybrid method for concrete and steel reinforcement. Wen et al. (2014) compared a conventional four-storey apartment Johor Bahru and a four-storey IBS apartment in Iskandar Malaysia, Johor. Bin Marsono and Balasbaneh (2015) compared seven different building materials for wall construction of a single-family unit house in Johor, but only global warming potential (GWP) was measured.

1.2 Research Problem

LCA studies in Malaysia were conducted without considering full building life cycle or 'cradle-to-grave' which consist of pre-use, construction, use, and end-of-life (EOL) phases. Moreover, full environmental impact on residential buildings in Malaysia has yet to be evaluated. Therefore, there is a need to quantify and improve the impact of buildings on the environment from cradle-to-grave in Malaysia.

1.3 Research Aims and Objectives

The aims of this research are to assess the environmental impact potential in the development of residential buildings in Malaysia and to identify critical areas in the system that have the potential for improvement. This research also aims to identify and quantify the possible improvement of the implementation of green building criteria for a conventional residential building. The objectives of this research are:

i. To evaluate and establish a benchmark of conventional residential buildings in Malaysia in term of its environmental impact for the whole life cycle using LCA.

ii. To evaluate the environmental impact of an energy efficient residential building in Malaysia by using LCA and compare with conventional residential buildings.

iii. To quantify the potential reduction of environmental impact of conventional residential building with Malaysian green building standard by using LCA and subsequently to estimate the potential of carbon emission reduction from the building industry in supporting Malaysian Government sustainable development initiatives.

1.4 Scope and Limitation

This research will focus on the application of life cycle assessment of residential buildings in Malaysia within the following scope and limitations:

i. Three (3) sample buildings were selected for case studies. Two (2) of the buildings are representative of conventional residential buildings in Malaysia in term of designs and materials specifications. The first building is a double-storey semi-detached government quarters (GQ) and the second building is a double-storey semi-detached house developed by a local property developer (PD), both located in Selangor. The third building is an energy efficient residential building (EEH) located in Melaka. EEH has been selected to assess the potential of reduction of energy and environmental impact in comparison to conventional residential buildings. The GQ and PD buildings were selected since the gross floor areas are comparable to the EEH and also due to the accessibility of complete documentations such as bill of quantities and construction drawings.

ii. The biggest constraint in conducting an LCA in Malaysia is the insufficiency of background data (Subramaniam, 2009). Classified data and trade secrets will limit the data required for this research. For this reason, local data will be used where possible. Other sources such as public databases, published literature, and LCA software databases will be utilised in the absence of local data.

iii. Green Building Index (GBI) Assessment Criteria for Residential New Construction (RNC) version 3.0 guidelines will be used as the reference standard. Only selected GBI criteria will be simulated to the case studies buildings as this research is limited to the system boundary as specified in Chapter 3.

1.5 Significance of the research

Since the introduction of LCA in Malaysia, its implementation in the building industry is very limited. As far as we know, there is no complete LCA study conducted in

Malaysia for the whole building life cycle from cradle-to-grave. This research attempts to evaluate and set up a benchmark of the environmental impact of the residential buildings in Malaysia from cradle-to-grave. Subsequently, this research tries to quantify the potential reduction of environmental impact with the Malaysian green building standard. The findings from this research can validate the significant improvement of the environmental impact of the residential building by the implementation of green building standard in Malaysia in line with the National Green Technology Policy. This research also tries to estimate the potential reduction of carbon emission of residential buildings whether it can contribute to the 40% emission intensity reduction, pledged by the Prime Minister of Malaysia at the United Nations Climate Change Conference 2009.

1.6 Methodology of the research

This research evaluates the environmental impact of three residential buildings in Malaysia from cradle-to-grave. The LCA methodology is based on ISO 14040 series; which consist of four stages, namely goal and scope definition, life cycle inventories (LCI), life cycle impact assessment (LCIA) and interpretation. The functional unit selected is 1 m^2 of gross floor area, and the building lifespan is 50 years as suggested by previous research.

The data for LCI for pre-use phase will be obtained from the bill of quantities and adjusted to additional 5% for waste during construction. Data for operation phase for GQ and PD will be simulated by using Openstudio, an energy simulation software, as there are no energy data available. Energy data for EEH is based on actual data provided by the owner. The data for maintenance is based on replacement of selected building elements based on literature. The next stage is the LCIA where the data collected in the LCI, will be assessed by using SimaPro software. The results will be compared to other research for validation.

The results from LCIA will be used to identify critical areas for improvement. Subsequently, selected Green Building Index (GBI) criteria will be applied to simulate the potential reduction of LCIA reduction for GQ and PD. The LCIA reduction specifically the Global Warming Potential (GWP) was used to estimate the potential carbon emission reduction for Malaysia.

1.7 Outline of the Thesis

This thesis is divided into five chapters. Chapter 1 briefly describes the introduction of this thesis, thesis aims and objectives and its scope and limitations. This chapter also highlighted the significance of the research and then briefly described the research methodology used.

Chapter 2 will discuss the related literature review. This chapter starts with the basic introduction to the sustainable development movement globally, in Malaysia and also in the building industry. This chapter also briefly discuss the general LCA methodology and later focus on the development of LCA in Malaysia. Then, this chapter briefly reviewed the application of LCA in the building industry including pertinent findings on previous research.

Chapter 3 outlines LCA methodology applied in this research. The four (4) LCA stages namely the goal and scope definition, LCI, LCIA, and interpretation were discussed and compared with published research. Subsequently, the findings were used to design suitable method for this research.

Chapter 4 reports the findings of the research based on the three (3) case studies. The specification of GQ and PD house were updated according to selected green building standards and EEH specification to quantify the potential energy and LCIA reduction.

Finally, Chapter 5 summarised and concluded the thesis with major findings and subsequently proposed recommendation for future research.

CHAPTER 2 : LITERATURE REVIEW

"We do not inherit the earth from our ancestors; we borrow it from our children." Chief Seattle

2.1 Sustainable Development – At a Glance

Sustainable development is defined in the United Nations' Our Common Future report (or Brundtland Report) as the development that meets the needs of the present, without compromising the ability of future generation to meet their needs (World Commission on Environment and Development, 1987). Later, various campaigns were introduced by the UN to promote the sustainable development agenda such as the Agenda 21 plan of action in 1992 in the UN Conference on Environment and Development (UNCED) and the World Summit on Sustainable Development in 2002 (Department of Economic and Social Affairs, 2006).

The introduction of the Millennium Development Goals (MDGs) in 2002 was intended to improve the life of millions of people with eight major goals. One of its goals is to ensure environmental sustainability by pushing every country to incorporate principles of sustainable development into their policies and programs by the year 2015 (United Nations, 2011). On 25th September 2015, the United Nations introduced the Sustainable Development Goals (SDGs) which follow and expand the previous MDGs. 17 SDGs have been outlined as shown in Figure 2.1. On 22nd April 2016, 175 countries signed the Paris Agreement on climate change and pledged to limit the global temperature rise well below 2 degrees Celcius, which is part of the SDGs and provides a roadmap to reduce emission and build climate resilience (United Nations, 2015).

Figure 2.1: 17 Sustainable Development Goals (United Nations, 2015)

In general, sustainable development is a process of change, whereby the exploitation of resources, the direction of investment, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspiration (World Commission on Environment and Development, 1987). The definition of sustainable development requires that we see the world as an interconnected system, whereby any actions taken by certain countries will create spin-offs to other countries; for example, the air pollution from North America affects air quality in Asia (IISD, 2013).

To achieve sustainable development, the other challenges that need to overcome is to reduce the impact of climate change. Scientists have concluded that climate change must be considered a plausible and severe probability, and each economic, social and environmental decision must take it into consideration (World Commission on Environment and Development, 1987). The introduction of Kyoto Protocol in 1997 under the United Nations Framework Convention on Climate Change (UNFCCC) was established to fight climate change, thus supporting the sustainable development agenda. The protocol has bound 37 countries and European communities to take action on global warming and greenhouse gas emission by 2012 (United Nations Framework Convention on Climate Change, 2011).

2.2 Sustainable Development in Malaysian Context

2.2.1 *Introduction*

Since the independence in 1957, Malaysia has grown from a raw material producer to leading exporter of electrical and electronics products, palm oil, natural gas and tropical timber (Hezri & Nordin Hasan, 2006; World Bank, 2013b). Due to the demand of timber, coupled with the agricultural development of rubber and oil palm, Malaysia is experiencing in rapid loss of rainforest. Hezri & Nordin Hasan (2006) has identified four major causes of environmental impacts in Malaysia:

- Impact on waterways: Poor control of mining resulted in deserted mining land, deterioration of rivers draining mining areas including high sediment loads rivers. The river system is also polluted by effluent from rubber and palm oil mills.
- Clearing of land: The booming of rubber demand in the 1900s resulted in deforestation to accommodate rubber plantation including new roads, tracks, and settlements.
- Increasing deforestation: The introduction of the Federal Land Development Authority (FELDA) responsible for significant impact including hydrological changes and erosion, pesticide contamination, pollution of mill effluent and extinction of local flora and fauna.
- The rise of manufacturing: Manufacturing dominated the Malaysian economy in the mid-1990s, therefore, attracting people to move to urban areas. The rapid urbanization is causing environmental problems in domestic waste management

and water supply. The river also being polluted by untreated effluent from factories and domestic.

In order to manage and improve the environmental conditions, the Environment Quality Act (EQA) 1974 was introduced by the Malaysian government to set up a legal framework for pollution control under the Ministry of Natural Resources and Environment (NRE) (Mohamed Noor et al., 2009). The EQA contains guidelines related to water quality, air quality, noise and waste management.

Later in 1985, Environmental Impact Assessment (EIA) had been introduced by the same ministry and was made mandatory in 1988 in Malaysia (Briffett, Obbard, & Mackee, 2004; Moduying, 2001; Vun & Latiff, 1999). The purpose of implementation EIA is to oversee the development process and its environmental consequences to the surrounding area. EIA provides a mechanism for preventive action in the early stage of the development, and the final reports will inform the decision maker on the best environmental alternatives available (Ho, 1992).

The implementation of EIA is however only mandatory for large development project within stipulated activities, subject to EIA under the Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order, 1987 (DOE Malaysia, 2011). Recent studies suggested that some EIA reports submitted were not up to standard and that the effectiveness of the implementation of the EIA in Malaysia is debatable (Memon, 2000; Vun & Latiff, 1999).

The issues of climate change are also being handled closely by the Malaysian government by the introduction of the National Policy on the Environment in 2002 and the National Policy on Climate Change in 2009 (by the NRE), including the National Green Technology Policy in 2009 under the Ministry of Energy, Green Technology and Water (KETTHA). These published policies serve as the framework for the government agencies, industries and community to improve the environmental management and climate change for sustainable future (NRE, 2013).

Moreover, at the United Nations Climate Change Conference 2009, The Prime Minister of Malaysia announced that Malaysia is adopting an indicator of a voluntary reduction of up to 40 percent in emissions intensity of GDP (gross domestic product) by the year 2020 compared to 2005 levels (BERNAMA, 2009). Since the pledged by the Prime Minister, Malaysia has made considerable preparation to achieve the target including the integration of renewable energy, energy efficiency and solid waste management in the 10th Malaysia Plan, implementation of clean development mechanism (CDM), development of a road map for a 40% reduction of carbon emission intensity and also voluntary carbon offset scheme involving the corporate sector (Lian, 2010).

2.2.2 *Overview of Current Malaysia's Energy Scenario*

2.2.2.1 Energy supply and demand

Malaysia has transformed from an agriculture based to the industrial based producer. With this transformation, the increase in power demand is inevitable. According to research by Malaysian Industrial Energy Efficiency Improvement Project (MIEEIP), Malaysia's energy consumption per unit of Gross Domestic Product (GDP) is high in comparison to most developing countries in the ASEAN region. Malaysia's final energy demand has increased significantly from the year 1978 to 2011 especially for diesel, motor petrol, electricity and natural gas (refer Figure 2.2).

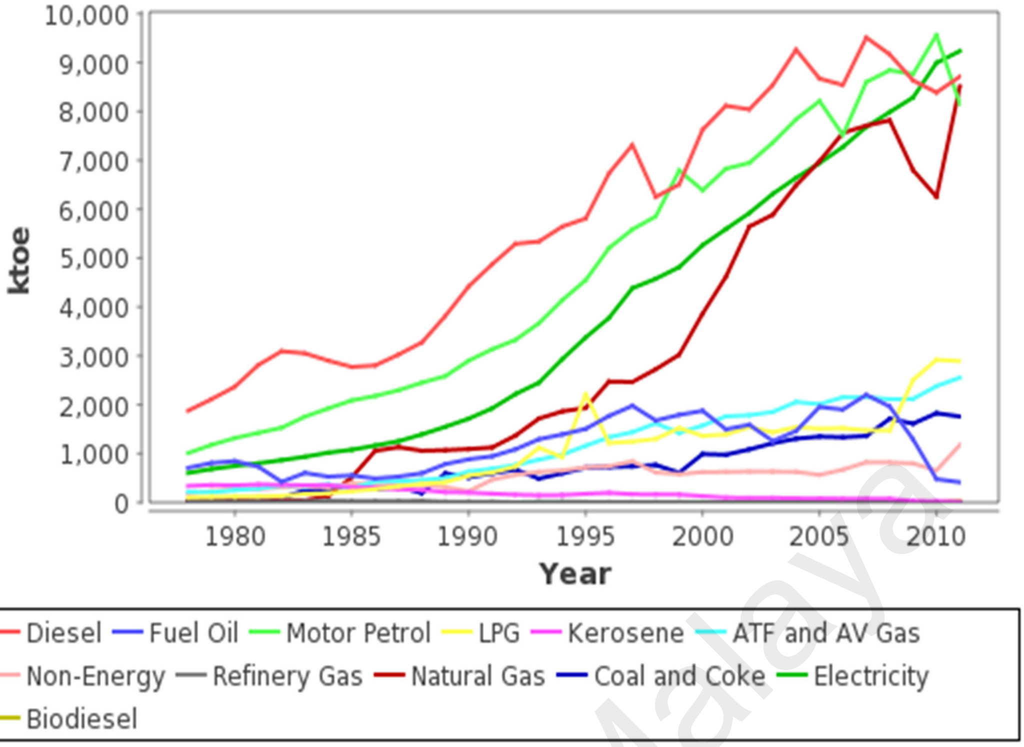


Figure 2.2: Malaysia's final energy demand from 1978 to 2011

(Suruhanjaya Tenaga, 2013)

In 2011, the largest energy demand by fuel type is electricity (at 21.3%) although in general, sources from petroleum products is still the highest with 55.1% of total energy demand (Suruhanjaya Tenaga Malaysia, 2013a). Regarding final energy demand by sectors, the transportation is the highest at 39.3%, followed by the industrial sector at 27.8%, residential and commercial at 16.1%, the non-energy sector at 14.7% and agriculture at 2.1%. Total final energy demand in 2011 increased by 4.8% from 2010 due to growth in the non-energy sector by 72.5%, 4.2% in the residential and commercial sector and 1.4% in the transport sector. Overall, the transport and the industrial sector remains the largest consumer of energy.

Table 2.1: Final energy demand according to sector in 2011

	Thousand tons of oil equivalent (ktoe)	Percentage (%)
Industrial[1]	12100	27.8
Transport[2]	17070	39.3
Agriculture[3]	916	2.1
Non-Energy[4]	6377	14.7
Residential and Commercial[5]	6993	16.1

Source: Suruhanjaya Tenaga (2013)

Note:
[1]Ranging from manufacturing to mining and construction. Diesel sales through distributors are assumed to be to industrial consumers
[2]Basically refers to all sales of motor gasoline and diesel from service stations and sales of aviation fuel. It also includes diesel and motor gasoline sold directly to government and military
[3]Covers agriculture, forestry, and fishing
[4]Use of products resulting from the transformation process for non-energy purpose (i.e. bitumen/lubricants, asphalt/greases) and use of energy products (such as natural gas) as industrial feedstocks
[5]Not only refers to the energy used by households and commercial establishments but includes government buildings and institutions

2.2.2.2 Electricity Supply and Consumption

Electricity demand is growing as the economy surges. Malaysia's total available generating capacity as at the end of 2011 was at 28.75 GW, which of the installed capacity, 9% are in Sarawak, 6.7% in Sabah and 84.3% in Peninsular Malaysia (Suruhanjaya Tenaga Malaysia, 2013a). In Malaysia, electrical are generated by various approaches that can be summarised in Figure 2.3.

The usage of fossil fuel in generating electricity is still significant in Malaysia which responsible for high GHG emission and climate change. In 2009, Malaysia was the second largest of CO_2 emission per capita in the ASEAN region after Brunei (World Bank, 2013a). The potential of renewable energy as the alternative sources of electricity is being reviewed and implemented by the Malaysian government under the Ministry of Energy, Green Technology and Water (KeTTHA) to promote green technology in line with the Prime Minister's pledged.

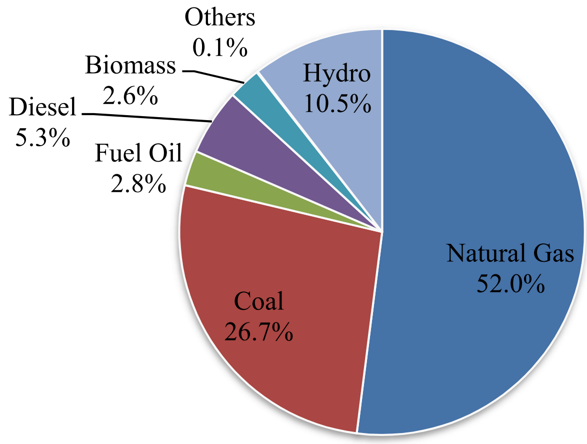


Figure 2.3: Electricity generation according to various method in 2011 (Suruhanjaya Tenaga Malaysia, 2013a)

2.2.3 *Malaysia Green Technology Effort*

KeTTHA was restructured from Ministry of Energy, Water, and Communications (MEWC) in April 2009 with the vision to be the industry leader in sustainable development and green technology. In August 2009, KeTTHA launched the National Green Technology Policy (Figure 2.4), to provide direction and motivation for sustainable development in terms of awareness, research, and development, marketing and commercialisation of green technology which span from 10th Malaysia Plan to 12th Malaysia Plan and beyond (KeTTHA, 2013). KeTTHA has also identified four (4) key areas for major improvement which are:

- Energy sector

  The use of green technology in power generation and energy supply side management and energy utilization sectors.

- Building sector

  Adoption of green technology in the construction, management, maintenance and demolition of buildings.

- Water and waste management sector

  Adoption of green technology in the management and utilization of water resources, wastewater treatment, solid waste and sanitary landfills.

- Transportation sector

  Incorporation of green technology in the transportation infrastructure and vehicles, in particular, biofuels and public road transport.

The restructuring of Pusat Tenaga Malaysia (PTM), or Malaysian Energy Centre to Green Technology Corporation (GreenTech) in August 2009 acted as the implementing arm of KeTTHA in pursuing the National Green Technology Policy (GreenTech, 2013). GreenTech will provide services in term of consultancy, research and training to achieve the goals set in the National Green Technology Policy. Other projects and programmes that are highlighted in green technology are tabulated in **Table 2.2**.

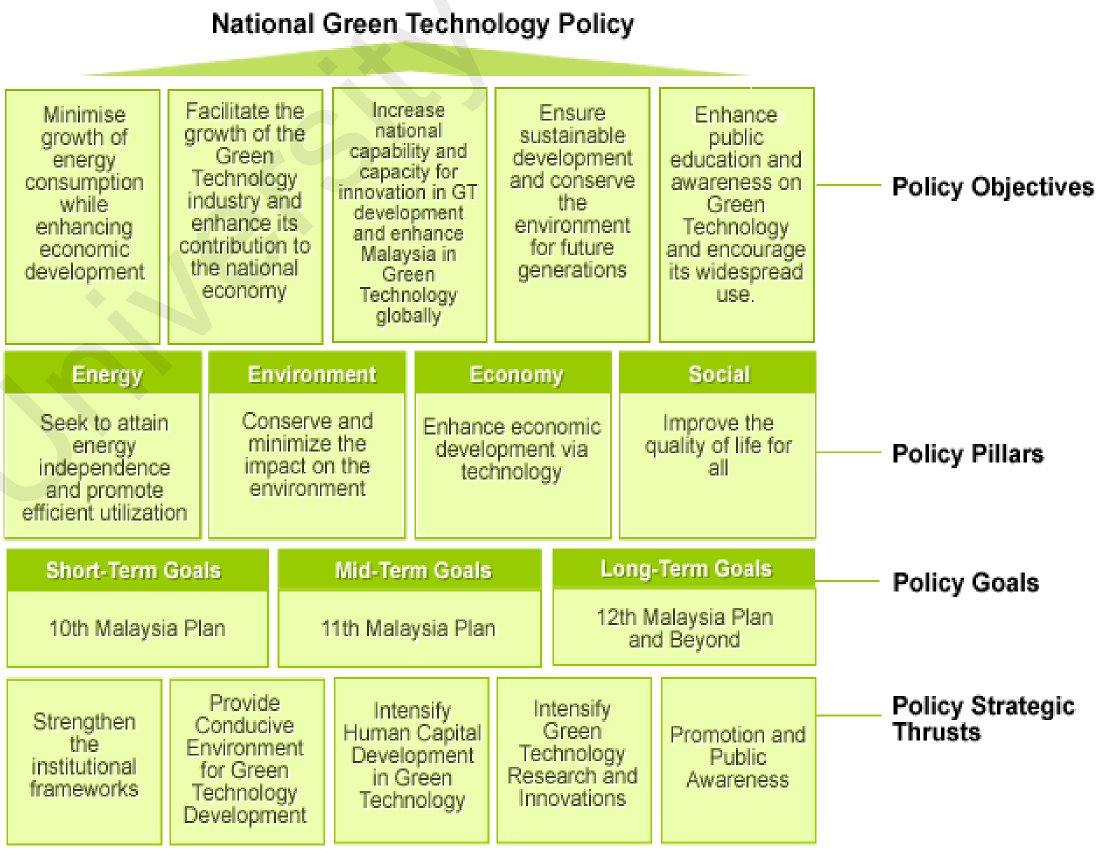


Figure 2.4: National Green Technology Policy (KeTTHA, 2013)

Table 2.2: Projects and programmes under the National Green Technology Policy KeTTHA (2013)

	Project/Programmes	Functions
1.	National Green Technology and Climate Change Council (MTHPI)	To formulate policies and identify strategic issues in National Green Technology Policy development and climate change
2.	Green Technology Financing Scheme (GTFS)	Allocation of RM 1.5 billion funds for green technology producers and users to make soft loans to finance activities
3.	Eco-Labelling	Collaboration of SIRIM and GreenTech to encourage the business sector to create environmentally friendly products
4.	Green Township	Ministry initiatives to create a green township in Putrajaya and Cyberjaya based on National Green Technology Policy
5.	Green Technology Studies	The action plan of National Green Technology Policy by focusing on Infrastructure Masterplan and Electric Vehicles Roadmap
6.	Smart Partnership	To strengthen the National Green Technology policy by creating green jobs, integrating green topics in schools and higher education syllabus, green ICT, and cooperation with South Korea on green technology.

2.2.4 *Overview of Malaysia's Building Industry*

The Malaysian construction industry is one of the major drivers of Malaysian economic. It has produced job opportunities and influences the development of social and economic infrastructure (Anuar et al., 2011). Currently, the construction industry is booming with 14.7% expansion in the first quarter of 2013 lead by the civil engineering and building projects (JPM, 2013).

Malaysian construction industry can be divided into four (4) work specialisation namely building, civil engineering, electrical and mechanical. In 2011 up to June of 2013, building projects contributed more than half of the total projects awarded in Malaysia (CIDB, 2013a). A building project can be divided into two (2) sub-sectors namely residential and non-residential. Between this two sub-sector, the non-residential projects surpass the residential projects in term of the number and value of the projects (CIDB, 2013a).

According to statistics published by Construction Industry Development Board Malaysia (CIDB), in 2011, the highest number of non-residential projects and value are retail (973 projects worth RM11.1 billion) and industrial buildings (697 projects worth RM19.0 billion) respectively; for residential projects predominantly are terrace housing projects with 672 projects worth RM7.1 billion (CIDB, 2013b).

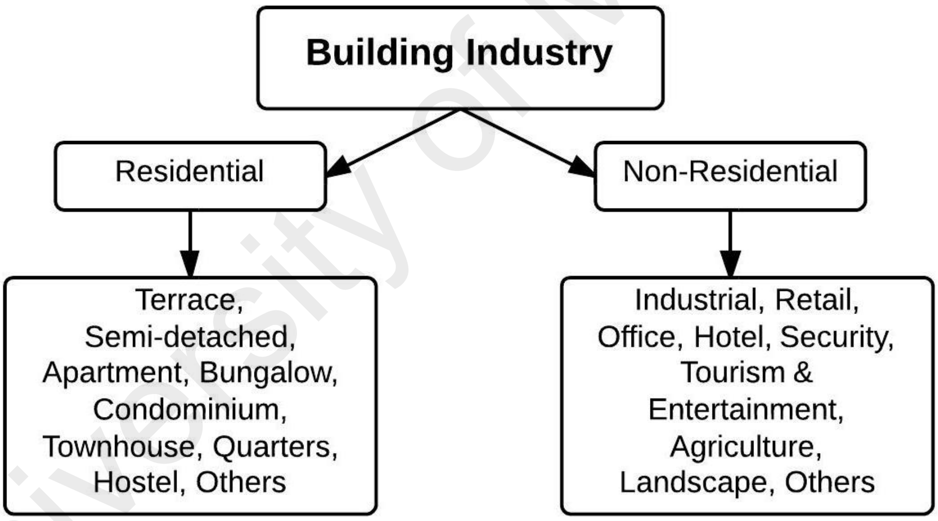


Figure 2.5: List of building types according to CIDB (2013b)

Since buildings have been identified to have the largest potential for GHG emission reduction, numerous measures have been put in place by the Malaysian government to promote the concept of sustainable and energy efficient buildings in the industry.

2.2.5 *Sustainable Development Initiatives in the Building Industry in Malaysia*

In order to regulate and minimize the impact of building to the environment, various Malaysian government bodies have initiated various programmes even before the introduction of the National Green Technology Policy.

2.2.5.1 MS 1525:2007 Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-residential Buildings

The MS 1525:2007 guidelines is the updated version of the MS1525:2001, which had started as the Guidelines for Energy Efficiency in Non-Domestic Buildings in 1989 by Ministry of Energy, Communication and Multimedia (now known as KeTTHA) (Zain-Ahmed, 2008). The technical committee of the guideline came from various local professional bodies, building related organisations, related government departments, universities and also Danish International Development Agency. The MS 1525:2007 was planned to be adapted to the Malaysian Uniform Building By-Laws (Zain-Ahmed, 2009). The purpose of the MS 1525:2007 is as follows:

- To encourage the design, construction, operation and maintenance of new and existing buildings in a manner that reduces the use of energy, without constraining creativity in design, building function and the comfort of productivity of the occupants; appropriately dealing with cost consideration;
- To provide criteria and minimum standards for energy efficiency in the design of new buildings, retrofit of existing buildings and methods for determining compliance with these criteria and minimum standards;
- To guide energy efficiency designs that demonstrate good professional judgement to comply with minimum standards; and

- Encourage the application of renewable energy in new and existing buildings to minimise reliance on non-renewable energy sources, pollution and energy consumption while maintaining comfort, health, and safety of the occupants.

2.2.5.2 Malaysia Building Integrated Photovoltaic (MBIPV) Project and Suria 1000

The MBPIPV project is a cooperation of the Malaysian Government with co-financing from the Global Environment Facility and through the United Nations Development Programme (UNDP), which was launched on the 25th July 2005 and completed on 31st May 2011 (MBPIV, 2013). The main objective of the project is to reduce the cost of building integrated photovoltaic technology in Malaysia and promoting the potential of renewable energy as an alternative for power generation.

In 2007, Suria 1000 programme under MBIPV was launched with the idea to install 1000 kWp of BIPV in Malaysia with discounted price (PTM, 2004). BIPV technology was installed in government buildings such as in Low Energy Office (LEO) building and Energy Commission Diamond building in Putrajaya and GreenTech Green Energy Office (GEO) in Bangi.

2.2.5.3 Feed-in Tariff (SEDA)

Feed-in Tariff (FIT) system introduced by the Sustainable Energy Development Authority (SEDA) is the continuity from MBIPV project. FIT was introduced in April 2010, and the process is still ongoing. The FIT system enables the Feed-in Approval Holders to sell the electricity generated from renewable energy from biogas, biomass, small hydropower and small photovoltaic system with a fixed premium rate (SEDA, 2013). The duration is based on the type of generating system; 16 years for biomass and biogas resources; 21 years for small hydropower and photovoltaic resources. To finance the FIT system, SEDA has established a renewable energy fund which directly comes from the consumers by increasing the electricity tariff by 1% (L. H. Yee, 2011)

Since the introduction, SEDA has received a total application of 1,480 of which only 960 applications approved for installation up to 2015, and from the application, 96% are for solar PV installations (Muhammad-Sukki et al., 2014). The FIT programme also has attracted local and foreign investors especially in the solar industry which indirectly creates job opportunities for Malaysians (Muhammad-Sukki et al., 2014). The introduction of FIT has significantly increased the potential of implementing renewable energy in Malaysia and making it less dependent on the fossil fuels in electricity generations (Wong, Ngadi, Abdullah, & Inuwa, 2015).

2.2.5.4 Green Building Index

The Green Building Index (GBI) is a voluntary scheme, co-developed by Pertubuhan Akitek Malaysia (PAM) – Malaysian Institute of Architects – and Association of Consulting Engineers Malaysia (ACEM) officially launched on 21st May 2009 (PAM, 2009). The GBI was derived from existing rating tools, which include the Green Mark from Singapore and Green Star from Australia, but being extensively modified for Malaysian tropical weather, environmental context, cultural and social needs (Green Building Index, 2009).

The GBI system evaluates six (6) main criteria including energy efficiency, indoor environment quality, sustainable site planning and management, material and resources, water efficiency and innovation as shown in Table 2.3. The system is reated to promote sustainable development in the building industry. The final result of the assessment will be rated with Platinum (86+ points), Gold (76 to 85 points), Silver (66 to 75 points) and Certified (50 to 65 points).

Table 2.3: GBI Rating System Criteria (Green Building Index, 2016)

GBI Criteria	Scope
Energy Efficiency (EE)	Improve energy consumption by optimising building orientation, minimizing solar heat gain through the building envelope, harvesting natural lighting, adopting the best practices in building services including use of renewable energy, and ensuring proper testing, commissioning, and regular maintenance.
Indoor Environment Quality (EQ)	Achieve good quality performance in indoor air quality, acoustics, visual and thermal comfort. These will involve the use of low volatile organic compound materials, application of quality air filtration, proper control of air temperature, movement, and humidity.
Materials & Resources (MR)	Promote the use of environment-friendly materials sourced from sustainable sources and recycling. Implement proper construction waste management with storage, collection, and re-use of recyclables and construction formwork and waste.
Sustainable Site Planning & Management (SM)	Selecting appropriate sites with planned access to public transportation, community services, open spaces, and landscaping. Avoiding and conserving environmentally sensitive areas through the redevelopment of existing sites and brownfields. Implementing proper construction management, storm water management and reducing the strain on existing infrastructure capacity.
Water Efficiency (WE)	Rainwater harvesting, water recycling, and water-saving fittings.
Innovation (IN)	Innovative design and initiatives that meet the objectives of the GBI.

The application of GBI is not limited to residential buildings but spans non-residential buildings, industrial building, retail building, and township. The buildings are divided into two categories, namely new and existing construction except for residential and township that only focus on new construction. Each category has different weighting points allocation set in the predetermined six (6) criteria as shown in Figure 2.6. The highest allocation of points in residential category is on the SM while others in EE.

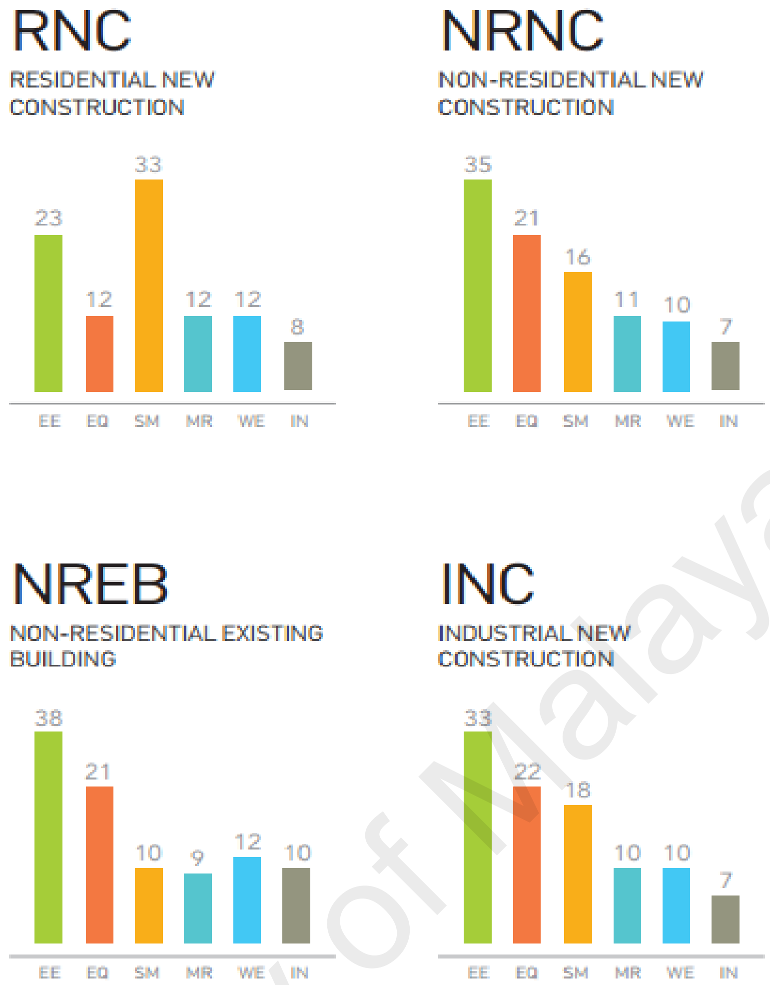


Figure 2.6: Different Weighting of Criteria According to the Type of Building (Green Building Index, 2016)

Since launch in 2009 to July 2013, a total of 146 projects has been certified, with the majority of the project is for non-residential new construction (72 projects), followed by residential new construction (61 projects) (Green Building Index, 2013b). Among notable projects awarded with Platinum awards are the Energy Commission building (Diamond building) in Putrajaya, SP Setia Berhad Corporate Headquarters in Shah Alam, Kompleks Kerja Raya 2 (KKR 2) in Kuala Lumpur, Bangunan Perdana Putra in Putrajaya, S11 House in Petaling Jaya and Tun Razak Exchange township in Kuala Lumpur.

Overall, the introduction of GBI does promote the idea of sustainable buildings, although most the projects were concentrated in the urban areas in Kuala Lumpur, Selangor, and Penang. It is estimated that the GBI certified buildings capable of reducing the CO_2 emission by 243,789 tonne CO_2 per annum (Green Building Index, 2013b). However, recent research has identified that there are barriers to the implementation of GBI that need to be overcome such as lack of awareness and technical understanding, the perception of higher cost, insufficient supply of green products, and lack confidence in the sustainable options (Algburi, Faieza, & Baharudin, 2016).

2.2.5.5 Construction Industry Development Board (CIDB)

CIDB was established under the Construction Industry Development Act (Act 520) to coordinate the Malaysia's construction industry, by planning the direction, handling the issues pertaining the industry, recommend the suitable policies, monitoring contractors and also overseeing the quality of construction outputs (CIDB, 2013b). Since 1999, CIDB has initiated the Green Technology programme by introducing six (6) working groups to oversee on good environmental practices. In 2010, CIDB established four (4) working groups to monitor the best green technology practices in the construction industry.

Since the establishment of the working groups, various research and development (R & D), publications and training modules have been developed. Among the important developments are the introduction of Industrialized Building System (IBS), green labelling for building products known as CIDB Green Label and also building rating system known as Green PASS (Bernama, 2012). IBS is a system where the building components are manufactured in a controlled environment, transported and assembled with minimal site work. The advantages of IBS are the minimization of waste and transportation frequency and also a manpower reduction requirement thus reducing the dependency to foreign labour (Anuar et al., 2011).

The Green Labelling scheme will encourage the manufacturing of environmentally-friendly construction materials and will be overseen by Construction Research Institute of Malaysia (CREAM), a subsidiary of CIDB (Bernama, 2012). The Green PASS is another building rating tool similar to GBI. Unlike GBI, Green PASS will assess throughout the whole building life cycle and expected to launch by the end of 2013 (The Edge, 2013).

2.2.5.6 Penarafan Hijau (pH)

Penarafan Hijau (pH) is a building rating system developed by Cawangan Alam Sekitar Dan Tenaga (CAST) or the Environment and Energy Department from JKR specifically to assess the government buildings (CAST, 2013a). This system is the integration of green initiatives conducted previously under JKR. Currently, the pH system is in its infancy stage and in the process of disseminating the information to all the JKR staff in the JKR Headquarters and all state offices (CAST, 2013b; Terengganu, 2012).

2.2.5.7 Centre for Environment, Technology, and Development, Malaysia (CETDEM)

CETDEM was founded on 25th April 1985 is an independent, non-profit, training, research, consultancy, referral and development organisation focusing environment, energy, technology, organic farming and development (MESYM, 2011). In 2004, an energy efficient renovation project was initiated by CETDEM to its office, which is an intermediate terrace house located in Petaling Jaya, funded by the Danish International Development Agency (DANIDA) (CETDEM, 2011a). After the renovations, the house incorporates solar panel as the source of renewable energy, rainwater harvesting system and the improvement of thermal comfort inside the house as shown in Fig. 2.7. After completing the renovations, the house shows an improvement in overall thermal comfort, energy and water usage.

CETDEM has also organised the Awareness & Building Capacity of Sustainable Energy Lifestyle among Urban Household project (ABC) project in April 2003 to June 2006, which was funded by UNDP Global Environment Facility (GEF) (CETDEM, 2011b). The objective of this project was to compile energy audits of five hundred (500) households in five (5) different Malaysian towns. Subsequently, The Working with the Community on Energy Efficiency at Household Level in Petaling Jaya (WCPJ) project funded by ExxonMobil was initiated as a continuation of the ABC project (CETDEM, 2011b).

Unlike ABC project that only focuses on an energy audit, the WCPJ has attempted to educate the participants on energy efficiency and propose an action plan and also to re-audit the energy after the action plan has been executed. Overall the WCPJ has managed to reduce up to 2,750 kWh. Both ABC and WCPJ projects have identified that in average, petrol for vehicles has the highest energy consumption, and air-conditioning has the highest electricity consumption in a household.

Figure 2.7: CETDEM Demonstration house in Petaling Jaya (CETDEM, 2011a)

2.3 Sustainable Development in the Building Industry

The relationship between the building industry and environmental pollution is continuously discussed in close association. While building industry is crucial for social and economic development, the impact on the environment from the processes involved are very significant. Roodman et al. (1995) suggested that buildings are responsible for 17% of world's freshwater withdrawals, 25% of wood harvest and 40% of its material and energy flows. Other researchers have also identified that buildings all over the world, are responsible for 30 to 40% of energy usage and 40 to 50% of world greenhouse gas (GHG) emission (Asif, Muneer, & Kelley, 2007; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009). Although most GHG emission is coming from buildings energy consumption, buildings also contribute to the emission of halocarbons, CFCs, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) (UNEP-SBCI, 2009).

Building industry consists of numerous phases starting from mining, manufacturing, construction, usage and demolition. In each phase, a substantial amount of energy is consumed, and at the same time, a significant emission is released. Energy is consumed directly during building construction, use and demolition while indirectly through the production of materials (embodied energy) used in the building (Sartori & Hestnes, 2007).

Most research has identified that the use phase is the largest energy consumer. Between 1971 and 2004, the carbon dioxide emissions have grown at a rate of 2.5% per year for commercial buildings and 1.7% per year for residential buildings (Levine et al., 2007). However, the building industry has the largest potential for significantly reducing GHG compared to other industry for both developed and developing countries by an estimated 30 to 80% throughout the building lifespan (UNEP-SBCI, 2009). The introduction of rating tools to the building industry helps to push the idea of sustainability to the industry players including the building users.

2.3.1 *Sustainable Rating Tools in the Building Industry*

Due to the significant impact of the buildings on the environment, various sustainable indicators have been introduced in recent years. The main purpose of the indicators is to promote the reduction of energy and GHG emission, by improving the building design, incorporating energy efficiency equipment, incorporating recycled building materials, and promote better site planning and management (Green Building Index, 2012).

The first building sustainable was developed by Building Research Establishment Environment Assessment Methodology (BREEAM) in the 1990s in the UK and later with Leadership in Energy & Environmental Design (LEED) that become the generic guidelines in other rating tools available worldwide (Green Building Index, 2009). Figure 2.8 shows the building rating tools available worldwide.

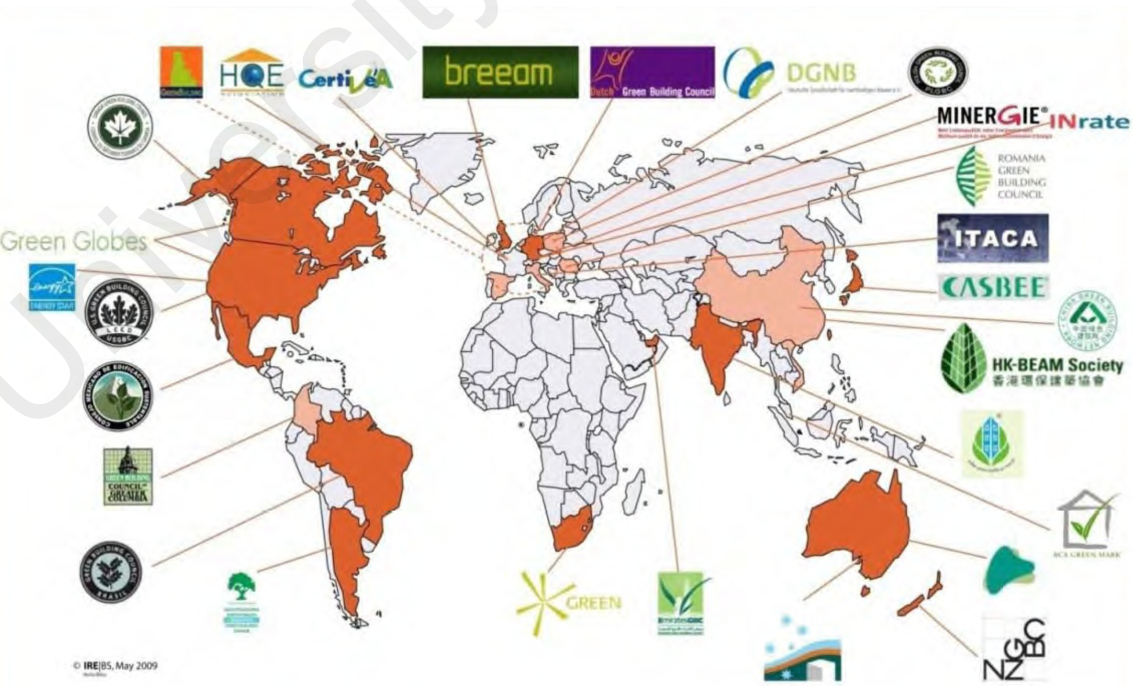


Figure 2.8: Building Rating Tools Available Worldwide
(Reed, Wilkinson, Bilos, & Schulte, 2011)

Currently, there are more than 600 sustainable rating systems offered throughout the world, and the numbers are kept growing as new systems are being introduced and regularly updated (Berardi, 2012). Although numerous rating system available, the most advanced and leading rating tools available are BREEAM (Building Research Establishment's Environmental Assessment Method) in the UK, LEED (Leadership in Energy and Environmental Design) in the US, CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) in Japan, Green Star in Australia and HK-BEAM in Hong Kong (Nguyen, 2011).

The rating methods developed with these tools are built upon various principles and different evaluation items, data, and criteria, based on the original condition of the buildings without taking consideration of a lifetime parameter such as a modification of the building elements (MD Darus & Hashim, 2012). The weighting systems are being formulated according to different environmental categories; then the points will be summed into a single final score that represents overall ratings. Although most rating systems have almost similar environmental categories, the value of each weighting is different. Saunders (2008) has tabulated a comparison of weighting system of four major rating systems as shown in Table 2.4.

Table 2.4: Weighting comparison of environmental issue categories in building rating system (Saunders, 2008)

	BREEAM	LEED	Green Star	CASBEE
Management	15	8	10	It is not possible to calculate the value of each issue category, for CASBEE, as the value is dependant on the final score
Energy	25	25	20	
Transport			10	
Health and Wellbeing	15	13	10	
Water	5	5	12	
Materials	10	19	10	
Landuse and Ecology	15	5	8	
Pollution	15	11	5	
Sustainable Sites	-	16	-	

Although all building rating systems have the same objective, the implementation of each system is different. Xiaoping et al. (2009) have identified four significant differences namely:

- Most rating systems developed in the West are initiated by a non-profit organisation while in the East are initiated by the government.
- The rating systems introduced in developed countries were designed according to market acceptance, therefore, resulted in higher penetration in the market compared to the system in developing countries.
- The flexibility of each tool is different, and the ability to be tuned according to different regions is a major trend around the world.
- The weighting system was not included in some of the rating systems which resulted in lacking scientific value

Since the introduction of the building rating system in the market, Malaysia under the Pertubuhan Akitek Malaysia (PAM) or the Malaysian Institute of Architects and the Association of Consulting Engineers Malaysia (ACEM) has launched Green Building Index (GBI) in 2009 to help to promote the sustainable building agenda in Malaysia.

2.4 Background of Life Cycle Assessment

Proper tools and method can contribute to quantify and compare the environmental impact of supplying products and services to achieve sustainable development (Rebitzer et al., 2004). LCA has been defined as a systematic analysis to measure industrial processes and products, by carefully examining the flow of energy and materials consumption, waste released into the environment, and also evaluate alternatives for environmental improvement (Fay et al., 2000; Guinée, 2002; Utama & Gheewala, 2009; Wu et al., 2010). LCA has been accepted internationally, and it can be implemented in a wider field, including in the building industry (Fava et al., 2009; Ortiz et al., 2009).

The first life cycle assessment (LCA) reportedly started in the 1960s, where the work was mainly focused on calculating energy requirements or “fuel cycle” by the Department of Energy in the United States (US) (Curran, 1996). Some authors suggested that Coca-cola was the first one who conducted an LCA in 1969 for a multi-criteria study to compare between using glass and plastic bottles, then modernize over the years which later developed in a series of ISO standards in the late 1990’s (Hunt et al., 1993; Ove Arup & Partners Hong Kong Ltd, 2007). In general, the ISO 14000 series published in the late 1990’s are accepted as an agreed framework for LCA with ISO 14040 (on principal and framework), ISO 14041 (on goal and scope definition and inventory analysis), ISO 14042 (on LCIA) and ISO 14043 (on interpretation) (Rebitzer et al., 2004). In 2006, the new version of ISO standards was published replacing the prior version with 14040 and 14044 (replacing the ISO 14041, 14042, 14043) (Kestner, Goupil, & Lorenz, 2010). Guinée (2010) has distinguished three stages of the development of LCA:

- 1970 – 1990 Decades of conception: The scope of LCA studies was limited to energy analysis and broadens to the comparative analysis of packaging alternatives. The public interest LCA was rapidly growing in the early 1980s, but most research uses different methods without an agreed theoretical framework. Due to the different methods, the results were varied which hampered LCA from becoming an accepted assessment tool.
- 1990 – 2000 Decade of standardization: In this stage, LCA activities increase tremendously lead by Society of Environmental Toxicology and Chemistry (SETAC) producing LCA guides and handbooks including organising forums and workshops worldwide. While SETAC focus in development and harmonization of LCA methods, the formal task to standardise the LCA methods and procedures was done by the International Organization of

Standardization (ISO). At this stage, LCA research papers have been published in leading scientific journals and have also been included in the policy documents and legislation.

- The present of LCA – Decade of elaboration: After the standardization process, the introduction of Life Cycle Initiative by the United Nations Environment Programme (UNEP) and SETAC, the establishment of the European Platform on Life Cycle Assessment, and also the promotion of LCA by the U.S Environmental Protection Agency, clearly shows that the acceptance of LCA is increasing. Although most LCA research were conducted based on ISO, the divergence in approaches arise subject to system boundaries and allocation methods, dynamic LCA, spatially differentiated LCA and so on. Some researcher even incorporated the life cycle costing (LCC) and social aspect to the LCA.

2.4.1 *Basic Concept of Life Cycle Assessment*

LCA is a methodology framework to estimate and evaluate the environmental impact throughout the product life cycle from cradle-to-grave. (ISO, 2006a; Rebitzer et al., 2004). Society of Environmental Toxicology and Chemistry (SETAC) has previously identified four phases in LCA, namely goal, and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle improvement assessment (Consoli et al., 1993). Life cycle improvement later was omitted as a phase in ISO 14040, and being replaced with a life cycle interpretation that interacts with other phases (Rebitzer et al., 2004), as in Figure 2.9.

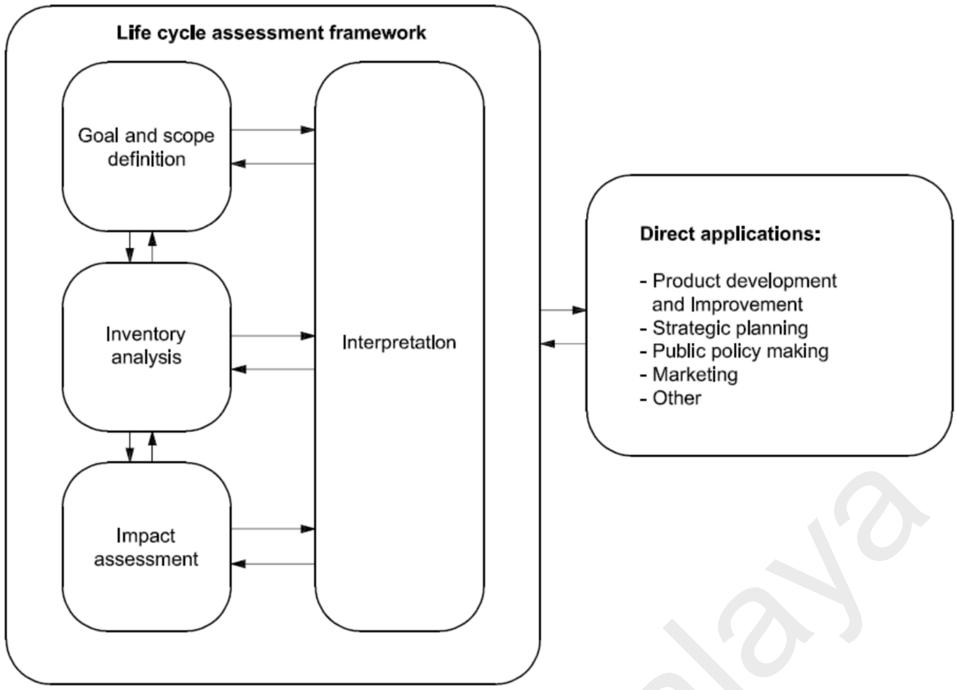


Figure 2.9: ISO 14040 LCA Framework (ISO, 2006a)

The first phase of LCA, which is defining goals and scopes, will determine the purpose of the study, system boundaries, and selection of suitable functional units. The second phase, which is life cycle inventory (LCI) is the data collection process of all relevant inputs and outputs of a product life cycle. The third phase, the life cycle impact assessment (LCIA) will use data from LCI and subsequently evaluates potential environmental impacts and estimate resource used in the study. The last phase is the interpretation that identifies significant issues, assesses results to reach conclusions, explain the limitations and provide recommendations.

Every product life cycle starts with the design and development of the product, followed by resource extraction, production, use or consumption and finally, end-of-life (EOL) activities such as waste disposal, recycling or reuse (Rebitzer et al., 2004). Every process in a product life cycle will have a different margin of impact to the environment in term of resource consumption and toxic emission as in Figure 2.10.

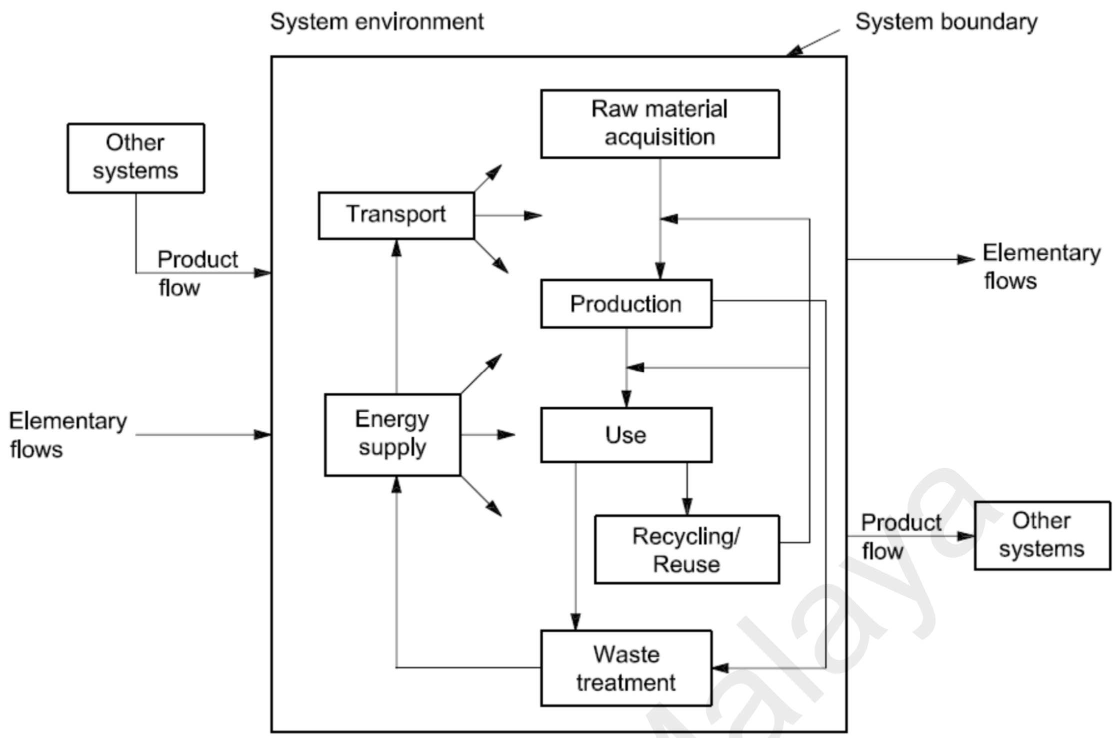


Figure 2.10: Example of a Product System for LCA (ISO, 2006a)

There are three (3) approaches in LCA research, namely: 1) Process-based LCA; 2) Economic Input-Output LCA (EIO-LCA), and 3) Hybrid LCA (Combination of process-based and EIO-LCA). Generally, process-based LCA is more complicated and time-consuming compared to EIO-LCA, nevertheless, the majority of the LCA research preferred the process-based method (Suh & Nakamura, 2007), including in the building industry (Abd. Rashid & Yusoff, 2012a).

EIO-LCA is based on economic input-output data, pollution discharges, and non-renewable resource consumption data of all industry sectors and being considered producing comparable results with process-based LCA (Hendrickson et al., 1997). The EIO-LCA web-based software www.eiolca.net was developed by Carnegie Mellon University's Green Design Initiative and can be used freely (Hendrickson et al., 1997; Ochoa, Hendrickson, & Matthews, 2002). However, at present, the EIO-LCA models are focused mainly in the US, Canada, Germany, Spain, and China only (Carnegie Mellon University Green Design Institute, 2011).

2.4.2 *Goal and Scope Definition*

2.4.2.1 General

The whole LCA process is guided by the direction set in the Goal and Scope Definition phase. This phase will help to maintain consistency of the LCA (Goedkoop, Schryver, Oele, Durksz, & Roest, 2010). The goal of the study is determined in terms of the exact question, target audience, and intended application; the scope of the study is defined in terms of temporal, geographical and technological coverage (Guinée, 2002; ISO, 2006b). According to ISO 14040 (2006a) and Goedkoop et al., (2010), in this phase the important preferences are described, such as:

- The reason for executing the LCA, and the questions that need to be answered
- A precise definition of the product, its life cycle, and the function it fulfills
- A description of the system boundaries
- A description of the way allocation problems will be dealt with
- Data and data quality requirements
- Assumptions and limitations
- The requirements regarding the LCIA procedure, and the subsequent interpretation to be used
- The intended audiences and the way the results will be communicated
- If applicable, the way a peer review will be made
- The type and format of the report required for the study

Occasionally, the goal and scope may be revised due to unforeseen limitations, constraints or additional information (ISO, 2006b).

2.4.2.2 System Boundary

The system boundary determines which processes should be included in the LCA and should be consistent with the goal of the study (ISO, 2006b). The system boundary normally illustrated by a general materials flow diagram that usually spread from cradle-to-grave, cradle-to-gate or gate-to-gate (Dixit, Culp, & Fernández-Solís, 2013). The cradle-to-grave comprise of the extraction of raw materials, manufacture of intermediate materials, manufacture of the product, use of the product and finally the disposal of the product (Curran, 1996). The boundary of the cradle-to-gate system is similar to the cradle-to-grave system, but it excludes the use phase and disposal of the product as shown in Figure 2.11.

Figure 2.11: Example of cradle-to-grave and cradle-to-gate system boundary (Science in the Box, 2013)

The gate-to-gate system boundary however only focuses on the production process of the product only. Within the system boundary, specific spatial (geographical) and temporal (time) boundary should also be included in the system boundary (Finnveden et al., 2009). There is also the allocation of 'cut-off' criteria with certain threshold percentage for initial inclusions of inputs and outputs for items which can be considered not contributing much to the overall impact on the environment (Goedkoop et al., 2010; ISO, 2006b).

2.4.2.3 Functional unit

The functional unit defines the quantification of identifying the functions of the selected product to ensure proper comparability (ISO, 2006a). It is also important that the chosen functional unit should be clearly defined and measurable (ISO, 2006b). To define a suitable functional unit can be difficult as the performance of products is sometimes not easy to describe (Goedkoop et al., 2010). The selection of functional units may vary even though the scope of the LCA is similar. Recent LCA research related to building, for example, have come out with numerous functional units. Most researchers uses one square meter (1 m^2) of gross floor area (GFA) as a functional unit but some researchers added a variation to the functional unit by specified a certain number of occupants in the building and the other only reflected in the heated areas only. Therefore, it is crucial to identify the suitable functional unit from previous research to obtain accurate results to meet the LCA goal and subsequently contribute the results as a reference for future research.

2.4.3 *Life Cycle Inventory (LCI)*

LCI is the phase where it compiles inputs and outputs related to the functions and products generated from all processes within the stipulated boundary in the first phase (Rebitzer et al., 2004). This phase is considered to be the most difficult task and most labour and time consuming in the preparation of an LCA research (Finnveden et al., 2009; Goedkoop et al., 2010; Rebitzer et al., 2004). According to Goedkoop et al. (2010), there are two types of data required in this phase:

i. **Foreground data**: refers to specific data needed to model the system. Typically, the data that describe a particular product system or a particular specialised product system.

ii. **Background data**: data for generic materials such as energy, transport, and waste management system. This type of data can be obtained in the databases and literature.

The collection of foreground data will require a collection of data from the specific person in the related companies. The type of data may depend on the products itself. The most important data for buildings, for example, will be extracted from the bill of quantities or bill of materials available either from the quantity surveyor, contractor or the developer.

The background data will often consist of 80% of data needed to perform an LCA (Goedkoop et al., 2010). Databases for environmental assessment sometimes included in the LCA tools and others are available commercially such as Ecoinvent (Germany) and Malaysian Life Cycle Inventory Database (MY-LCID). Several databases are available for free, for example, US Life Cycle Inventory Database developed by the National Renewable Energy Laboratory (NREL), European reference Life Cycle Database (ELCD) developed by and Building for Environmental and Economic Sustainability (BEES) developed by the National Institute of Standards and Technology (NIST). Other than databases, the usage of literature also able to help researchers to obtain data which usually not available in the standard databases.

2.4.4 *Life Cycle Impact Assessment (LCIA)*

The LCIA is the next step in the LCA after the LCI. In this phase, the results from the LCI will be evaluated the potential environmental impacts (ISO, 2006a). Similar to the LCI phase, the selection of the method and the impact categories will be bound by the

Goal and Scope Definition (Goedkoop et al., 2010). Most LCA practitioners prefer to select the existing assessment methodologies that have been published rather than develop it from scratch (Goedkoop et al., 2010; ISO, 2006b). ISO 14044 (2006b) stated that the LCIA would consist of mandatory and optional elements as in Figure 2.12. However, in the existing assessment methodologies, most choices in the impact assessment as in Figure 2.12 are already determined (TOSCA, 2011).

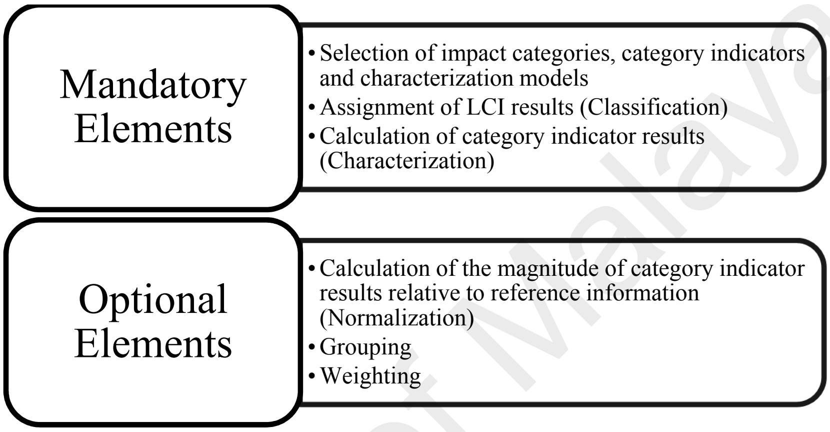


Figure 2.12: LCIA Elements (ISO, 2006b)

2.4.4.1 Selection of Impact Categories, Category Indicators, and Characterization Models

The selection of the appropriate impact categories should be guided by the goal of the study, and the related information and resources should be referenced (Goedkoop et al., 2010; ISO, 2006b). The list of items identified in the LCI data collection process will be interpreted in the LCIA into midpoints or/and endpoints such as the potential impact on human health, natural resources, natural environment and man-made environment (EPA, 2001; Finnveden et al., 2009; JRC, 2013).

Table 2.5: The definitions and examples of the term used in this step

Item	Term	Definition	Examples	Reference
1.	Impact Categories	Class representing environmental issues of concern to which LCI results may be assigned	Climate change, Ozone depletion, Acidification	(ISO, 2006a; Life Cycle Initiative, 2010)
2.	Category Indicators	Quantifiable representation of and impact category	Infrared radiative forcing, Proton release	(ISO, 2006a; Life Cycle Initiative, 2010)
3.	Characterization Model	Mathematical model of the impact of elementary flows on a particular category indicator (provide a basis for characterization factor)	IPCC model for climate change, RAINS model for acidifying substances	(Life Cycle Initiative, 2010)
4.	Characterization Factor	A factor derived from a characterization model that is applied to convert the assigned LCI results to the common unit of the category indicator	Global warming potential (GWP), Acidification Potential (AP)	(ISO, 2006a; Life Cycle Initiative, 2010)

ISO does not specifically suggest using certain endpoints, but the selection and definition of endpoint should be done carefully, and the impact linking to the impact categories should be clearly described (Goedkoop et al., 2010).

Table 2.6: Example of Impact Categories, Characterization Models, Factors, and units (Life Cycle Initiative, 2010)

Impact category	**Indicator**	**Characterisation model**	**Characterisation factor**	**Equivalency unit**
Abiotic depletion	Ultimate reserve/annual use	Guinee & Heijungs 95	Abiotic depletion potential	kg Sb eq.
Climate change	Infrared radiative forcing	Intergovernmental Panel on Climate Change	Global warming potential	kg CO_2 eq.
Stratospheric ozone depletion	Stratospheric ozone breakdown	World Meteorological Organization model	Stratospheric ozone layer depletion potential	kg CFC-11eq.
Human toxicity	Predicted daily intake, accepted daily intake	EUSES, California Toxicology Model	Human toxicity potential	kg 1,4-DCB eq.
Ecological toxicity	PEC, PNEC	EUSES, California Toxicology Model	AETP, TETP, etc.	kg 1,4-DCB eq.
Photo-oxidant smog formation	Tropospheric ozone production	UN-ECE trajectory model	Photo-oxidant chemical potential	kg C2H6 eq.
Acidification	Deposition/critical load	Regional Acidification Information & Simulation	Acidification potential	kg SO2 eq.

2.4.4.2 Classification

ISO 14044 define Classification as the assignment of LCI results that are exclusive to one impact category and identification of LCI results in more than one impact category that includes:

a) The distinction between parallel mechanisms (apportioned among several impact categories)

b) Assignment to serial mechanism (classified to contribute to several impact categories)

2.4.4.3 Characterization

The Characterization process is the calculation of indicator results involving the conversion of LCI results to common units and the aggregation of the converted result within the same impact category (ISO, 2006b). For example, 5 kg CO_2 and 3 kg CH_4 yield 68 kg CO_2 –eq (climate change) (Life Cycle Initiative, 2010).

2.4.4.4 Normalization

Normalization is the calculation of the magnitude of category indicator results relative to reference information (over a given period of time) for a specific area, person or product (ISO, 2006b; Life Cycle Initiative, 2010). The aim of this step is to understand better the relative magnitude of each indicator results of the product system under study (Life Cycle Initiative, 2010).

2.4.4.5 Grouping

Grouping is the assignment of impact categories into one or more sets as predefined in goal and scope and may involve sorting and ranking (ISO, 2006b). There are two (2) ways to group LCIA data (EPA, 2001; ISO, 2006b):

a) To sort the impact categories on a nominal basis (such as inputs and outputs or global regional and local spatial scales), or
b) To rank the impact categories in a given hierarchy such as high, low or medium priority

2.4.4.6 Weighting

Weighting is the process of converting and aggregating indicator results across impact categories using numerical factors (ISO, 2006b). Weighting steps are based on value choices and not based on scientific point of view. For example, the weighting factors can be in term of monetary values (willingness-to-pay, damage costs), distance-to-target methods and panel methods (expert panels, non-expert panels) (Life Cycle Initiative, 2010)

2.4.5 *Interpretation*

The last step in LCA according to ISO is Interpretation. The main objectives of Interpretation in ISO is as follows (ISO, 2006b):

a) The identification of the significant issues based on the results of the LCI and LCIA phases of LCA
b) An evaluation that considers completeness, sensitivity, and consistency checks
c) To reach conclusions, explain limitation and provide recommendations

The results will be interpreted according to the goal and scope of the study which shall include an assessment and a sensitivity check of the significant inputs, outputs, and methodological choices to understand the uncertainty of the results (ISO, 2006b)

2.5 Life Cycle Assessment in Malaysia

Although LCA has been implemented worldwide, the introduction of LCA in Malaysia is relatively recent. The Government of Malaysia under the Ninth Malaysian Plan has empowered SIRIM to initiate the National LCA Project to conduct life cycle assessment research, assist the National Eco-labelling Program and to comply with international standards to reduce the environmental impact of products and services throughout their life cycle (LCA Malaysia, 2009). Initially, the idea of LCA implementation is not so well received by Malaysian industry players as there was no demand for it, but it is slowly changing especially in biodiesel production from palm oil, which has to follow Directive of the European Parliament and the Council on the Promotion of the Use of Energy from Renewable Resources (Ismail & Chen, 2010).

Since the launched of National LCA Project, the number of LCA research has increased gradually. SIRIM has conducted numerous LCA research especially on the development of local LCI databases which resulting in the launching of Malaysian Life Cycle Inventory Database (MY-LCID). At the moment, MY-LCID has 166 datasets that can be used for LCA research and initiatives for a nominal fee (MY-LCID, 2013). Various local universities and research institutes have conducted research on LCA as summarised in Table 2.7.

Table 2.7: Published LCA research in Malaysia

University/Research Institute	Category	Reference
MPOB	GHG contribution in the palm oil supply chain	(Choo et al., 2011)
SIRIM	Bio-mate composting system	(SIRIM, 2011)
UKM	Fluorescent lamp ballast	(Syafa Bakri, Surif, & Ramasamy, 2008)
UM	Solid waste landfill siting	(Sumiani, Onn, Din, & Jaafar, 2009)
UM	Crude palm oil production	(Yusoff & Hansen, 2007)
UM	Formulation of LCA framework for Malaysia using the Eco - indicator	(Onn & Yusoff, 2010)
UM	Water treatment process	(Sharaai, Mahmood, & Sulaiman, 2009b)
UM	Potable water production	(Sharaai, Mahmood, & Sulaiman, 2009a)
UM	Clean Development Mechanism in palm oil industry	(Onn & Yusoff, 2012)
UM/MPOB	Milling process of palm oil	(Subramaniam, 2009)
UM/SIRIM	Eutrophication Potential of Laundry Detergent	(Thannimalay, Yusoff, Chen, & Zin Zawawi, 2012)
UM/SIRIM	Sodium Hydroxide	(Thannimalay, Yusoff, & Zawawi, 2013)
UM/SKU	Electricity generation from rice husk	(Shafie, T.M.I.Mahlia, Masjuki, & Rismanchi, 2012)
UPM/UKM	Solid waste disposal system	(Hassan et al., 1999)
USM	Palm biodiesel	(K. F. Yee, Tan, Abdullah, & Lee, 2009)
USM	Production of biodiesel from palm oil and jatropha oil	(Lam, Lee, & Mohamed, 2009)

University/Research Institute	Category	Reference
UTM	Industrialised Building System (IBS) house	(Balasbaneh & Abdul Kadir, 2012)
UTM/DTU	GHG reduction through enhanced use of residues in palm oil biodiesel	(Hansen, Olsen, & Ujang, 2012)
UTM/TUT	CO2 emission from housing	(Fujita et al., 2008)

Abbreviation:
UPM: University Putra Malaysia
MPOB: Malaysian Palm Oil Board
UTM: Universiti Teknologi Malaysia
USM: Universiti Sains Malaysia
UKM: Universiti Kebangsaan Malaysia
DTU: Technical University of Denmark
TUT: Toyohashi University of Technology (Japan)
SIRIM: Standard and Industrial Research Institute of Malaysia
UM: Universiti Malaya
SKU: Syiah Kuala Universiti (Indonesia)

2.6 Life Cycle Assessment Concept and Methodology in the Building Industry

In the last decade, research on LCA related to building industry has increased significantly in the manufacturing of building materials and construction processes. Buildings, in general, are more difficult to assess as they are massive, diverse materials and their production method are inconsistent because each building has a unique characteristic (Scheuer, Keoleian, & Reppe, 2003). The other significant limitation is that there is limited quantitative information about the environmental impact of the production and manufacturing of construction materials or the actual process of construction and demolition (Scheuer et al., 2003).

The LCA methodology applied in the building industry, however, is still in a fragmented state due to a variety of case study buildings with diversity in materials selection, locations, construction process, building design and usage that will produce a different definition of goal and scope and will bind to certain limitations (Abd. Rashid & Yusoff, 2012b).

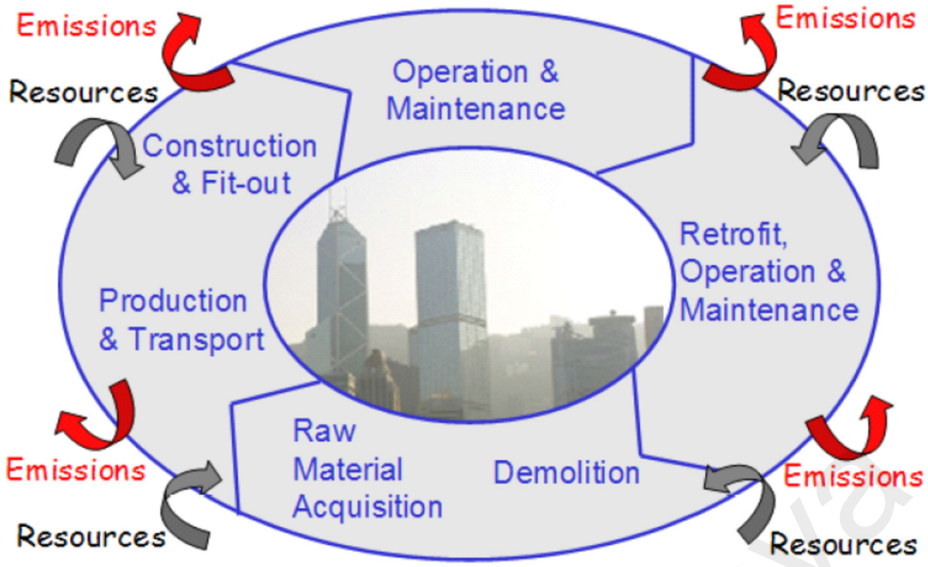


Figure 2.13: Life cycle phase of a typical building (Ove Arup & Partners Hong Kong Ltd, 2007)

Sometimes, the goal and scope can change due to unexpected problems encountered during the research (Khasreen, Banfill, & Menzies, 2009). Each research will respond to a predetermined system boundary, functional unit, building lifespan. Figure 2.14 is an example of an LCA framework for building. The LCA research methodology applied in the building industry will be discussed further in Chapter 3.

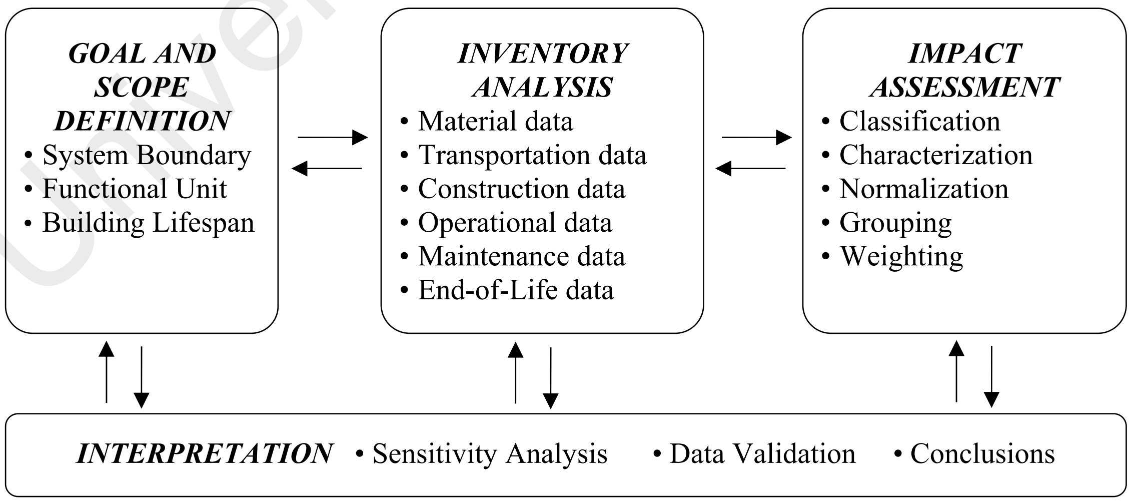


Figure 2.14: LCA framework for the building industry. Adapted from (G. A. Blengini & Di Carlo, 2010; ISO, 2006a; Ochsendorf et al., 2011; Ortiz-Rodríguez, Castells, & Sonnemann, 2010; Ove Arup & Partners Hong Kong Ltd, 2007)

2.7 Environmental Impact of Building from LCA research

2.7.1 *Impact of Different Building Phases*

Building phases can be separated according to the process involved during its life cycle (as in Figure 2.13). Most researchers found that the use phase of buildings contributed significant environmental impact due to its long periods of time. The emissions produced during the use phase is related to the fossil fuel combustion in electrical generation and also space heating (Scheuer et al., 2003).

Kofoworola & Gheewala (2009) identified that the use phase of a 60,000 m^2 office building in Thailand for a period of fifty years accounted for 81% of total energy consumption. Mithraratne & Vale (2004) conducted a comparison of three (3) construction type of residential building in New Zealand specifically the light construction, the concrete construction and the insulated construction and its use phase contributed 74%, 71%, and 57% respectively for one hundred years building life cycle. In Italy, a comparative research was conducted on low energy and standard house. The research suggested that the use phase in standard house contributed more than 80% total energy consumption compared to lower than 50% in low energy house (G. A. Blengini & Di Carlo, 2010).

A research on a new university building in Michigan, USA by Scheuer et al. (2003) identified that building operation represents 94.4% of total energy consumption. Ding (2007) has conducted a life cycle energy analysis of twenty (20) secondary schools in Australia for sixty years lifespan and suggested that operational energy in building use phase represent 62% compared to 38% in pre-use phase. Ooteghem & Xu (2012) conducted LCA research to five (5) single storey retail building in Canada for fifty years lifespan and identified that space heating consume the highest energy during building use phase (42%), followed by lighting (37%), ventilation fans (7%), space cooling (6%)

and miscellaneous equipment (6%). There are also other studies that produce similar results in which heating is the biggest energy consumer (G. A. Blengini & Di Carlo, 2010; G. Blengini & Di Carlo, 2010; Iyer-Raniga & Wong, 2012; Mithraratne & Vale, 2004; Zabalza Bribián et al., 2009). Nevertheless, buildings in a different location will produce a different energy use pattern. A building in the tropical region, for example, will have a different result from a building in a cold climate region as space heating is unnecessary.

2.7.2 *Impact of Material selection*

The selection of building materials will affect the total embodied energy during production. It also influences the total energy consumption in the use phase and the recycling potential.

Asif et al. (2007) suggested that concrete contributed 61% of initial embodied energy, followed by timber (13%) and ceramic tiles (14%) for residential building in Scotland. The study also suggested that the concrete has smaller initial embodied energy itself, but the amount of concrete used in the building is huge, thus responsible for the highest total embodied energy, similarly as reported in other studies (G. A. Blengini & Di Carlo, 2010; R. J. Cole, 1998). However, this research was only conducted for pre-use phase. Some study suggested that building material with low initial embodied energy may not typically have low life cycle energy (Utama & Gheewala, 2008, 2009).

Three identical design residential buildings were analysed using LCA with different core materials namely light construction (timber frame), concrete construction and light construction with superinsulated construction (Mithraratne & Vale, 2004). Concrete and superinsulated buildings produce higher initial embodied energy compared to light construction by 8% and 14% respectively. Both concrete and superinsulated buildings, however, have lower life cycle energy by 5% and 31% respectively than light construction. Insulated materials also were used to reduce thermal transmission in a low energy house in Italy (G. Blengini & Di Carlo, 2010), a green home in Australia (Fay et al., 2000) and a residential building in Netherland (Huijbregts, Gilijamse, Ragas, & Reijnders, 2003) that produced similar results. Recent research also suggested that residential buildings using Insulated Concrete Form (ICF) in the USA are more efficient during its life cycle compared to a light frame timber house with a similar design (Ochsendorf et al., 2011).

Buildings in a tropical climate with clay based products have been identified as a better alternative to cement based products. Utama & Gheewala (2008) concluded that the selected landed residential building in Indonesia using clay bricks and clay roof tiles, have better life cycle energy than cement based bricks and roof tiles due to lower thermal transfer thus preserving the cooling effect of air conditioning. Another research claim that high rise residential apartment using a sandwich wall of incorporating external clay brick, internal gypsum plasterboard, and air gap in between, have lower life cycle energy compare to single clay brick wall up to 59% (Utama & Gheewala, 2009).

López-Mesa et al. (2009) conducted an LCA research for two seven-story residential buildings with similar concrete based products but with different construction methods. Two systems were analysed namely in situ cast concrete floors and precast concrete floors. The advantage of the precast concrete floor system is the ability to have a longer span between beams thus minimises columns and footings. The reduction of columns and footings reduces total concrete used in the building. The environmental impact of precast concrete floors was estimated to be 12.2% lower than in situ concrete floors.

Recycling potential of building materials can reduce building materials embodied energy. An energy efficient apartment building in Sweden was analysed for a lifespan of fifty years, and the recycling potential can reclaim up to 15% of the total energy used (Thormark, 2002).

2.8 Summary

Sustainable development agendas have been pushed all over the world including in Malaysia. Numerous initiatives were implemented in Malaysia to reduce the environmental impact including in relation to the building industry. To quantify the environmental impact systematically, LCA has been introduced and has been accepted worldwide, however the implementation of LCA in the building industry is still being developed. The introduction of LCA in Malaysia is fairly new and the research related to buildings is very limited. The findings from LCA research on buildings can be divided into the impact of different building phases and different building materials used. Operation phases has been identified responsible for the highest energy consumption thus has significant impact environmentally. The usage of concrete in buildings contributed to significant total embodied energy compared to other building materials but by improving the concrete by added the insulated materials can produced better results.

CHAPTER 3 : RESEARCH METHODOLOGY

3.1 Life Cycle Assessment Method

3.1.1 *Goal and Scope Definition*

With reference to the first chapter, the goal of this research is to evaluate and set up a benchmark of the environmental impact of the conventional residential building in Malaysia from cradle-to-grave and tries to identify critical areas in the system which had the potential for improvement. This research also attempts to quantify the potential reduction of environmental impact the possible improvement of the implementation of green building criteria. A research design using case study methodology and LCA framework was developed to achieve the objectives, as shown in Figure **3.1** and Figure 3.2 respectively.

3.1.1.1 System boundaries

The whole building cycle will be evaluated from cradle-to-grave as in Figure 3.3. This research excluded the site clearance works, external works, and infrastructure works that involved the overall development and did not represent the case studies.

3.1.1.1.1Spatial boundary

The buildings selected for case studies are located in the central region of Malaysia. The energy simulation for estimating electrical consumption will use Kuala Lumpur weather data for the year 2013 obtain from US Department of Energy.

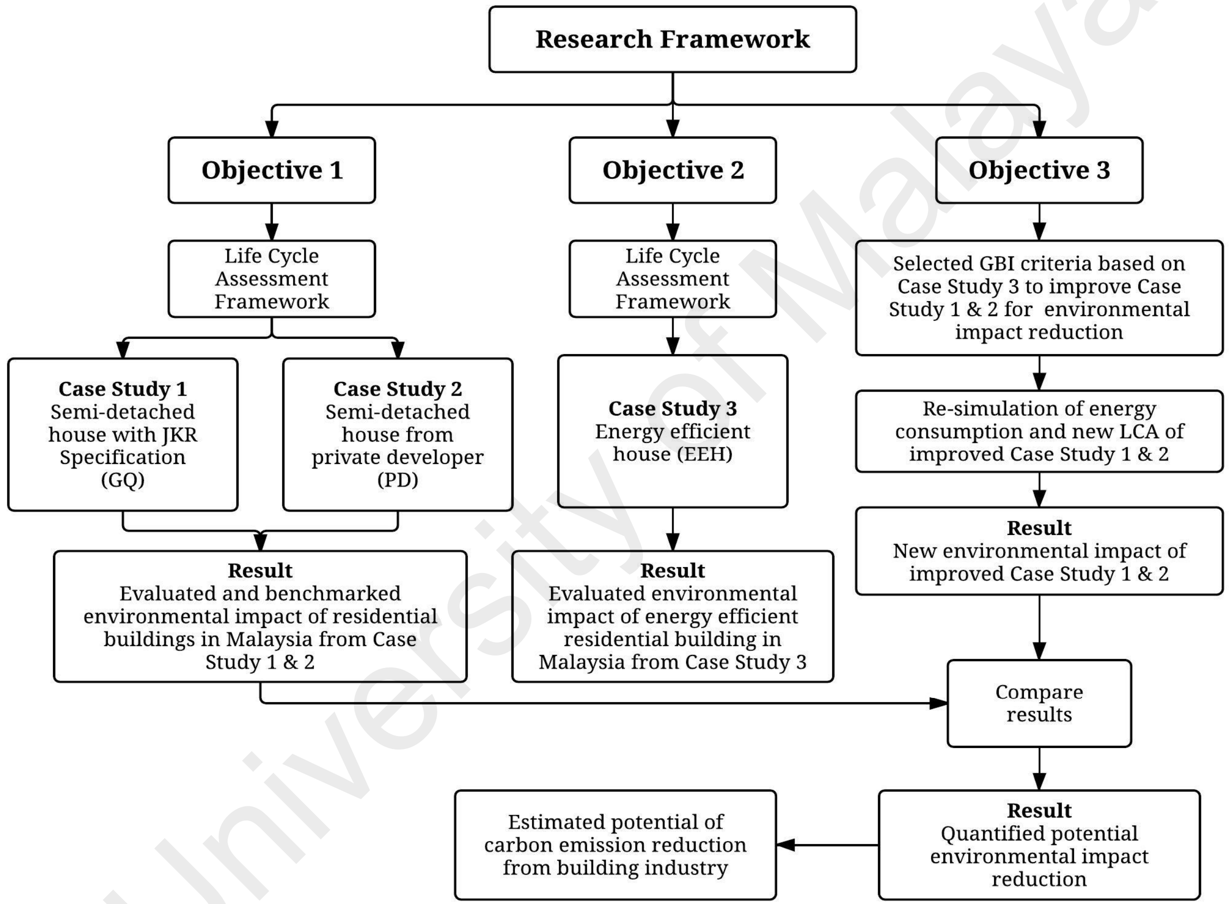


Figure 3.1: Research Framework

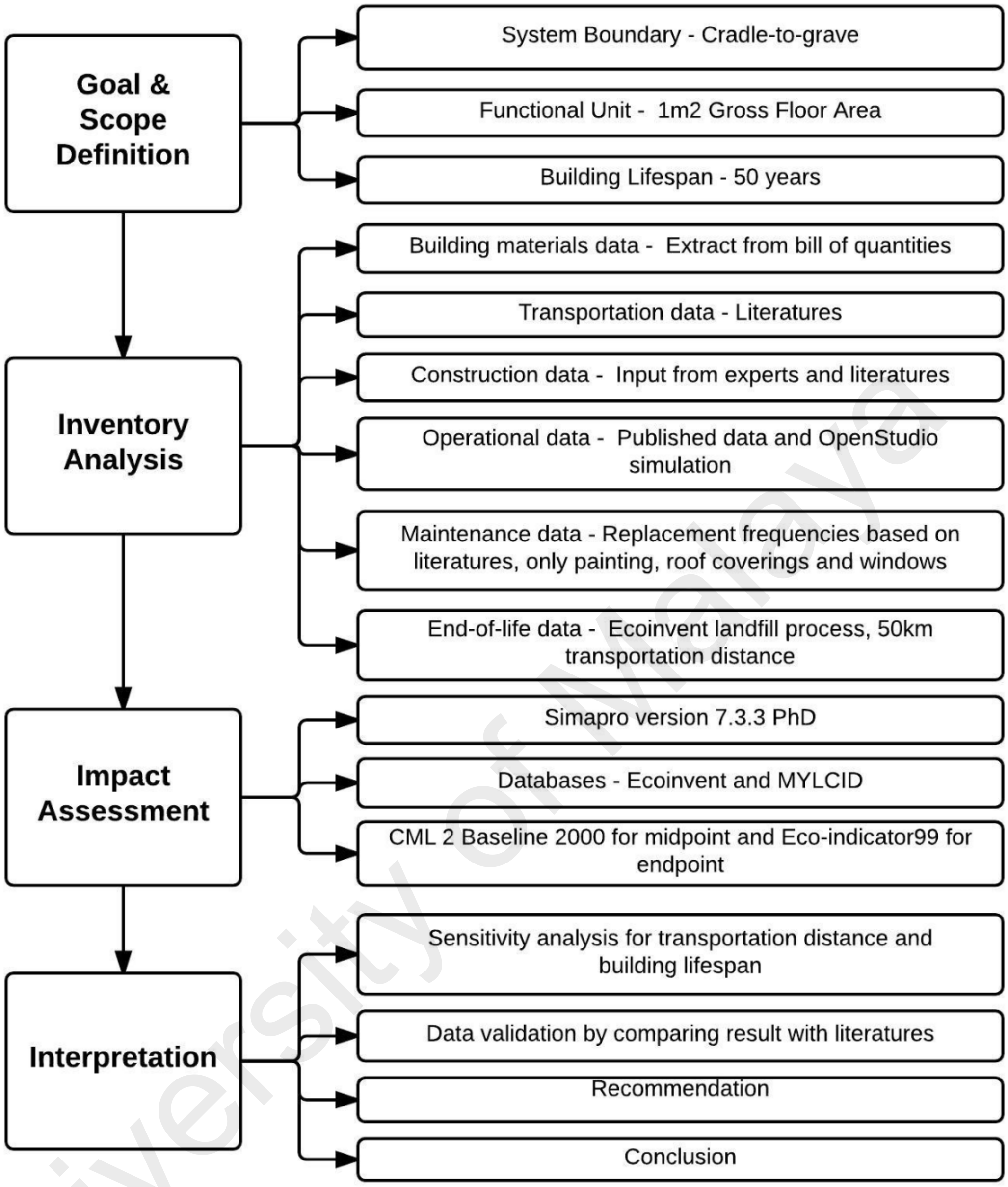


Figure 3.2: LCA Framework

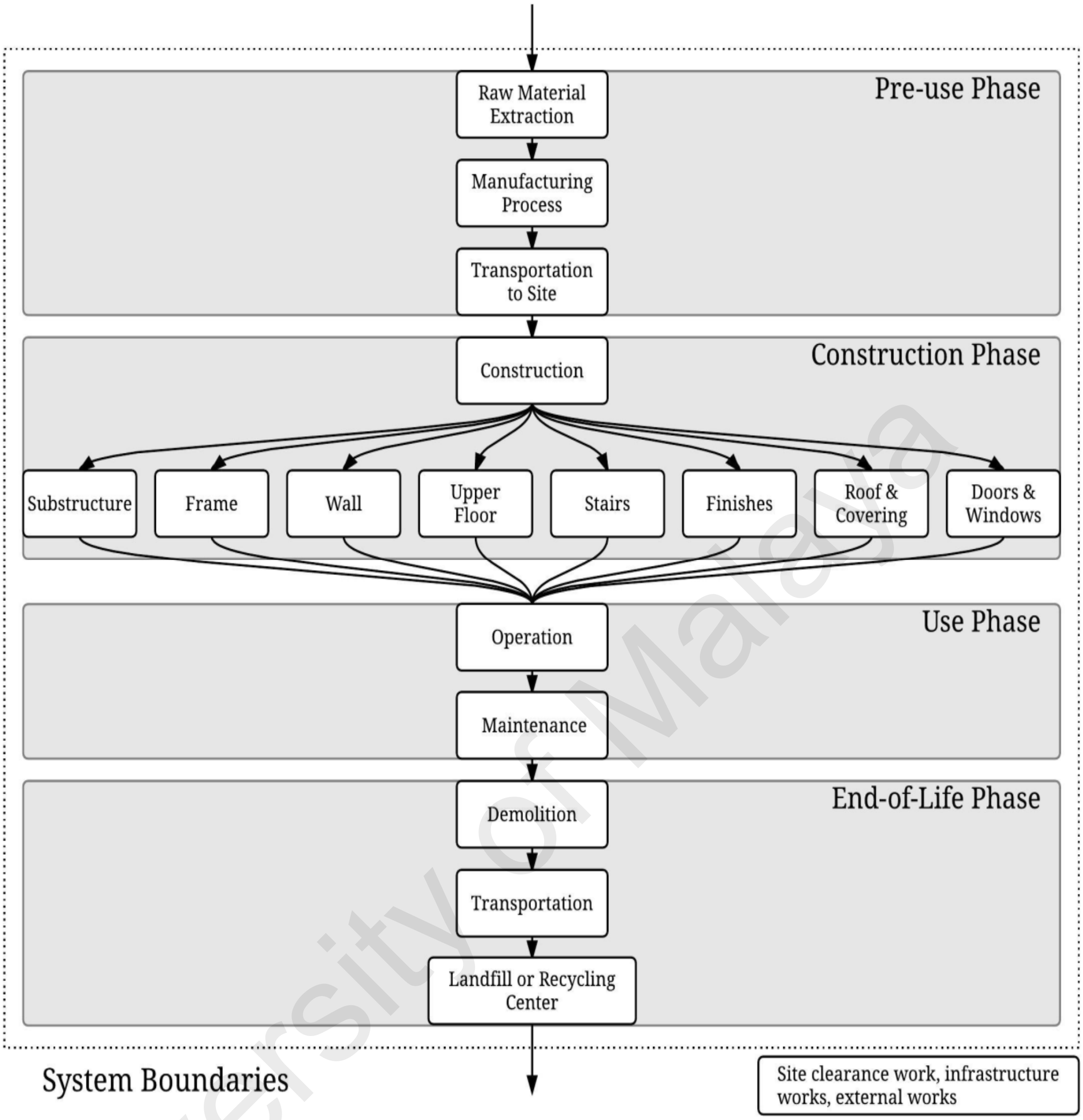


Figure 3.3: System boundaries used in this research

3.1.1.1.2Temporal boundary

Due to limitation and constraints in obtaining data for inventory, the case studies selected were built in different locations in different periods. However, since the chosen buildings are constructed in less than ten years apart and given that the construction methods and basic materials use (i.e. cement, brick, steel, and glass) are relatively similar, the author presumes that it is comparable.

3.1.1.2 Functional Unit

A suitable functional unit is difficult to be determined due to various materials and construction technologies applied to the buildings (American Institute of Architects, 2010). Common functional unit selected are based on the following studies (G. A. Blengini & Di Carlo, 2010; Cuéllar-Franca & Azapagic, 2012; Ochsendorf et al., 2011; Ortiz-Rodríguez et al., 2010; Wen et al., 2014), therefore the functional unit for this research is quoted in one square metre (1 m^2) of gross floor area (GFA) of building for comparison and for future references. The GFA is calculated based on total enclosed space fulfilling the functional requirements of a building measured to the internal face of enclosing walls, columns, door and the like (Ahmad, 2009).

3.1.1.3 Building Lifespan

In previous research in life cycle assessment (LCA) and life cycle energy assessment (LCEA), the lifespan of buildings is varied. The lifespan of residential buildings is assumed to be from 40 to 100 years but primarily 50 years are applied by researchers (Adalberth, 1997; Ortiz-Rodríguez et al., 2010; Rossi, Marique, Glaumann, & Reiter, 2012; Thormark, 2002; Zabalza Bribián et al., 2009). The 50 years lifespan was also widely used in other LCA research in commercial buildings (Arena & de Rosa, 2003; Cole & Kernan, 1996; Kofoworola & Gheewala, 2009; Van Ooteghem & Xu, 2012). Other research by Jabatan Kerja Raya (JKR) on the maintenance of government buildings also considers 50 year lifespan as its basis of calculation (Selvanayagam, Yusoff, Vithal, & Hamzah, 2006).

3.1.2 *Life Cycle Inventory*

3.1.2.1 Foreground Data

3.1.2.1.1Material Data

The data for building materials are obtained from the bill of quantities (BQ) or bill of materials (Iyer-Raniga & Wong, 2012; Monahan & Powell, 2011) or from estimated quantities of building drawings and field-measured data (G. A. Blengini & Di Carlo, 2010). Other researchers did not specify which method of data collection, but the important finding in this stage is to determine the type and the quantity of materials used in the building. This research will use bill of quantities to determine the materials used.

3.1.2.1.2Transportation Data

Different methods were used to determine transportation data. A few researchers used average transportation distances from factories to construction site based on communication with the designer and contractor (G. A. Blengini & Di Carlo, 2010) or selected by the nearest manufacturer and national averages (Ochsendorf et al., 2011). (Ortiz-Rodríguez et al. (2010) alternatively use assumptions to determine the distance between manufacturer to the building site.

The distances for transportation for this research will follow guidelines suggested by Wittstock et al. (2012). The distance for material transportation is considered to be 300 km to the construction site. The supply of ready-mix concrete, however, is considered to be 50 km distance from the concrete batching plant as the concrete will be unfit to use after a few hours. Due to the nature of buildings where the operational phase produces the largest environmental impact, transportation phase has a relatively low share of total emissions of CO_2 (Monahan & Powell, 2011; Rossi et al., 2012; Wittstock et al., 2012).

3.1.2.1.3Construction Process Data

Previous research have identified that the construction phase only contributed a relatively low share of total environmental impact (G. A. Blengini & Di Carlo, 2010; Ochsendorf et al., 2011; Rossi et al., 2012). Some researcher neglected the construction data to be included in the analysis but consider the waste generated during the process (Rossi et al., 2012). Some research estimated that about 5% of material waste on site during construction due to the vulnerability of the products, mishandling of materials and unusable residuals due to inaccurate installation (Buchan, Fleming, & Grant, 2003; Rossi et al., 2012). Data for LCI extracted from drawings or bill of quantities, therefore, must include the material waste. Blengini & Di Carlo (2010) collected construction data and making assumptions from field measured data, communication from designer and contractor and literature. Monahan & Powell (2011) collected aggregate data from the off-site manufacturing process from manufacturing companies, waste generation, energy and fuels used on-site, but no detail records were available which make detail analysis unattainable. Some data were unavailable due to the confidentiality policy from the manufacturer. This research will include information about construction process from Malaysian literature and construction expert.

3.1.2.1.4Operational and Maintenance Data

Operational Data

- Electricity supply

  The electrical supply will be considered to remain constant during building life cycle (Iyer-Raniga & Wong, 2012; Ortiz-Rodríguez et al., 2010). No consideration was taken for any fluctuation in the energy balance.

- Electrical Equipment

Most researchers include the heating, ventilation, and cooling (HVAC) system, lighting, domestic hot water (DHW), electrical appliances and cooking in the analysis. Energy simulation software is being used to estimate annual electricity consumption such as DesignBuilder with EnergyPlus, (Ortiz-Rodríguez et al., 2010), EnergyPlus (Ochsendorf et al., 2011), Edilclima EC501 (G. A. Blengini & Di Carlo, 2010), COMFIE (Peuportier, 2001; Thiers & Peuportier, 2012), CHENATH (Fay et al., 2000), AccuRate (Iyer-Raniga & Wong, 2012), DEROB-LTH (Thormark, 2002), ECOTECT (Utama & Gheewala, 2008) and eQUEST (Van Ooteghem & Xu, 2012). Some software are subjected to certain languages, locality and required expert knowledge in CAD and programming. EnergyPlus has been widely reviewed and validated using ASHRAE/BESTEST evaluation protocol (Attia, 2011). Software like DesignBuilder and OpenStudio use EnergyPlus engine with Graphical User Interface (GUI) for user-friendliness for the non-professional user. The OpenStudio software will be used in this research to estimate the energy consumption.

Maintenance Data

Ortiz-Rodríguez et al. (2010) suggested maintenance activities included are painting, re-roofing, PVC siding, windows, replacing kitchen and bathroom cabinet. Replacement of electrical appliances and light bulb, the impact from house cleaning and wastewater was not included. Blengini & Di Carlo (2010) stated that little reliable data on building materials lifespan were available resulting in assumptions based on literature. Ochsendorf et al. (2011) recommended roof and window replacements and interior and exterior re-painting. Iyer-Raniga & Wong (2012) used data based on a report entitled "Study of Life Expectancy of Housing Components" produce by US-based National Association of Home Builders (NAHB) as its basis for maintenance pattern. Suggested maintenance by Ortiz-Rodríguez et al. (2010) and Ochsendorf et al. (2011) will be used as a guideline where maintenance activities will only include re-painting, roof covering replacement and also windows.

3.1.2.1.5End-of-Life (EOL) Data

EOL phase was rarely being incorporated previously, but recent research identifies that the ability of recycling potential of building materials will contribute to the reduction in life cycle impact (G. A. Blengini & Di Carlo, 2010). As a developing country, the demolition process for residential buildings hardly ever occurs in Malaysia. Recent research by Arham (2008) has identified that only steel and aluminium are being regularly recycled whereas other materials are transported to the landfill. Due to the above circumstances, this research will apply Ochsendorf et al. (2011) method with estimated transportation distances to Malaysian landfill and recycling facilities. The recycling benefits of steel and aluminium are allocated to the production of the recycled item by substituting raw materials as avoided product to scrap iron and scrap aluminium as input from technosphere respectively as suggested in SimaPro (PRé, 2015). Table 3.1 shows the summary of assumptions for EOL.

Table 3.1: Summary of Assumptions for End-of-Life Phase

Researcher / **Process**	(Ortiz-Rodríguez et al., 2010)	(G. A. Blengini & Di Carlo, 2010)	(Ochsendorf et al., 2011)	(Rossi et al., 2012)
Demolition/ dismantling	Evaluates energy consumed by machinery used during demolition	Selective dismantling of re-usable/ recyclable material Controlled demolition of building structure	Total demolition	All EOL stages (demolition, transport, re-use, recycling, disposal) not include non-metallic material
Waste	Waste generated during demolition	Operation for construction and demolition waste treatment	The majority of materials sent to landfill except steel and aluminium which are recycled. Half of concrete is assumed to be recycled into aggregate	
Transportation	Transportation to landfill	Transportation to recycle, re-use and landfill	Unspecified	
Recycling Potential	No	Yes	Yes	Yes
Data Collection	Unspecified for energy consumed. For materials may be from the total quantity of building materials.	Literature and unpublished data	Unspecified. For materials from total quantity materials. Energy consumption during demolition was not omitted.	

3.1.3 *LCA Software and Databases*

SimaPro and GaBi are among the established LCA software in the market and can be used in different regions by selecting appropriate data, although the software itself is intended for LCA practitioners (Trusty & Horst, 2005). For this research, SimaPro 7.3.3

PhD version will be used. SimaPro is equipped with multiple databases that can be used such as Ecoinvent, ELCD, USLCI databases and Industry 2.0. Due to the wide range of materials, construction techniques, locations, manufacturing differences, energy sources, supply assumptions, not a single database can be considered complete (Khasreen et al., 2009; Ortiz et al., 2009). Malaysia Life Cycle Inventory Database (MYLCID) was used in the LCI especially on raw materials such as cement and diesel to produce significant results for Malaysian scenario (MY-LCID, 2013). Due to data limitation, Ecoinvent database was used and adapted to Malaysian conditions by replacing the local electricity mix data set as suggested by Horváth & Szalay (2012).

3.1.4 *LCIA Impact Method*

Blengini & Di Carlo (2010) suggested that the selection of indicators is always subjective but must be consistent with ISO recommendations for LCIA method. There are two (2) methods in conducting LCIA, which is problem-oriented (midpoints) and damage-oriented methods (endpoint). Midpoints are considered to be a point in the cause-effect chain of a particular impact category after the LCI prior to the end point (Bare, Hofstetter, Pennington, & Haes, 2000).

Different researcher used different impact categories but most commonly used were global warming potential, acidification, ozone depletion and eutrophication (Khasreen et al., 2009; Ortiz et al., 2009). Ortiz et al. (2009) suggested that the mid-points can be assessed using CML 2001 baseline method, EDIP 97 and EDIP 2003 and IMPACT 2002+ while the end points can be evaluated using Eco-indicator 99 and IMPACT 2002+. Other researcher also applied CML method for mid-points such as (Allacker, 2012; Garcia Martinez, Llatas Oliver, & Navarro Casas, 2011; Horváth & Szalay, 2012; Ochsendorf et al., 2011; Ortiz-Rodríguez et al., 2010; Szalay, 2007) and Eco-indicator 99 (Kellenberger & Althaus, 2009; Szalay, 2007; Zabalza Bribián et al., 2009) for

LCIA. Most impact categories have been already available with most LCA software including the SimaPro.

This research will use CML 2001 baseline method for midpoint with a focus on Global Warming Potential (GWP) as building has been identified as one of the largest GHG contributors and also the largest potential for reduction of GHG (UNEP-SBCI, 2009). Other indicators in the CML selected are acidification, ozone depletion potential (ODP), eutrophication and human toxicity as suggested from the previous study. For endpoint method, Eco-indicator 99 will be used with a focus on human health (HH), ecosystem quality (EQ) and resources (R) as it is widely used for LCA research for buildings that enable us to compare findings from this research to previous research.

3.1.5 *Interpretation*

The final step in LCA is the interpretation of results where values from the impact assessment will be analysed for robustness and sensitivity to inputs (Ochsendorf et al., 2011) and conclusions are drawn with reference to the goals and objectives of the LCA (ASTM Standards E1991-05, 2005). Other than the sensitivity analysis, the evaluation will also will assess the completeness and consistency check (ISO, 2006b) Data validation also will be conducted by comparing to other published research (Ochsendorf et al., 2011) and also by conducting sensitivity analysis to evaluate the reliability of non-local databases (Iyer-Raniga & Wong, 2012).

The purpose of the completeness check is to verify that all relevant information for interpretation are available and complete (ISO, 2006b). In the ISO 14044, the process of completeness check identifies any missing or incomplete information which relates to the goal and scope of the LCA and shall be recorded and justify. The consistency check is a process to determine whether the assumptions, methods, and data are consistent with the goal and scope, which addressed the data quality, regional and/or temporal differences, system boundary and consistency of impact assessment (ISO, 2006b). This research will list down all assumptions and limitations in paragraph 4.2 in the next chapter. All justifications of the assumptions, methods, and data are based on LCA research and guidelines related to building industry and also subject to the availability data. The findings from this research will be compared to the other similar studies to detect any incomplete or erroneous data as suggested by (Guinée, 2002).

The sensitivity analysis is a process that recalculates the LCA based on the changes in assumptions that have been made. The purpose of this process is to get a better understanding of the magnitude of the set assumption (Goedkoop et al., 2010) and to established the robustness of the results with variations (Guinée, 2002). The sensitivity analysis for this research focuses on the assumptions on transportation distances of building materials and the building lifespan. The sensitivity analysis determined whether the selected assumptions in this research influenced the results.

This research conducted a data validation by comparison with published research, and the conclusions were drawn according to the objective in the goal and scope set earlier.

3.1.6 *Critical Review*

A critical review process is needed to ensure the quality if the research work complies with ISO 14040. This research will be evaluated by the internal and external examiners, and the results and methodology will be presented at conferences and published in journals.

3.1.7 *Reporting*

This research will be published as a thesis, and it will be available in the library for references.

3.2 Proposed Improvement Based on Findings and GBI Criteria

The Green Building Index (GBI) evaluates six (6) main criteria including energy efficiency, indoor environment quality, sustainable site planning and management, material and resources, water efficiency and innovation. This research only focuses on the energy efficiency criteria, specifically to the advanced energy-efficiency performance and renewable energy based on the GBI residential new construction (RNC) version 3 (Green Building Index, 2013a). The characteristics of EEH will be applied to GQ and PD to estimate the potential of environmental impact reduction.

Furthermore, two additional measurements will be assessed based on the GBI criteria namely the overall thermal transfer value (OTTV) and the U-value of the roof. OTTV is an index to measure the thermal performance of a building in W/m^2 and the U-value of the roof is to measure the rate of transfer of heat across the materials in W/m^2K (Hong Kong Institute of Architects, 2012; Hui, 1997). The lower the values, the better the building performs and the higher points given in GBI assessment. The evaluations of OTTV for GQ and PD will be calculated using building energy intensity tool software namely Building Energy Intensity Tool (BEIT) version 1.1.0 by ACEM (ACEM, 2015) and the estimations of U-value of the roof will be based on the thermal resistance (m^2K/W) of building materials in roof construction. The BEIT software is developed for use specifically tailored to Malaysian climate and is one of the software approved by GBI for assessment of energy efficiency (Amirrudin & Chew, 2012).

After applying the new specification, the GQ and PD will be re-simulated in the OpenStudio to estimate the potential reduction of energy. The new GQ and PD will also be assessed in the SimaPro with selected CML 2001 baseline method to estimate the potential reduction in environmental impact.

CHAPTER 4 : RESULTS AND DISCUSSION

4.1 Introduction

This chapter will describe the application of the LCA framework approach within three (3) case studies considering the different specification of each building. They are; 1) a house developed for government quarters (GQ); 2) a house developed by a private developer (PD); 3) an energy efficient house (EEH) by a private owner.

4.2 General boundaries and limitations

The following assumptions have been considered for this research:

a) The quantities extracted from the BQ were deemed accurate according to actual buildings.

b) The data for electricity in Malaysia is based on the database published by MYLCID (MY-LCID, 2013)

c) The types and materials are limited to process data equipped in the SimaPro databases. For example, ceramic tiles used in the projects might be different in term of compositions and manufacturing process as to the ceramic tiles process data available in the SimaPro.

d) The various materials and manufacturing process for steel roof trusses and steel roof coverings (in GQ and EEH) are not available in the SimaPro databases except for the main material that is low-alloyed steel. The combination of materials that include zinc, aluminium and magnesium coatings including manufacturing process were subject to proprietary rights (Lysaght, 2015a, 2015b; TongYong Metal, 2015). Therefore, only the manufacturing process of low-alloyed steel and transportation were taken into consideration.

e) The process data for acrylic emulsion paint that is used in all case studies are not available in the SimaPro databases, therefore, being substituted with alkyd paint.

f) An additional of 5% of material waste during construction were considered from the total quantities from the BQ.

g) In Malaysia, steel and aluminiums are being regularly recycled, and other materials are transported to the landfill (Arham, 2008). The building materials related to steel and aluminium i.e. the reinforcement bars, aluminium window and door frames in the case studies were adjusted accordingly by replacing the used of pig iron and primary aluminium to scrap iron and old aluminium scrap respectively as suggested in the SimaPro.

h) The distance from manufacturer to the construction site was 300 km for general materials and 50 km for ready-mixed concrete (Wittstock et al., 2012).

i) A 16-ton lorry was used to transport materials from manufacturers to site whereas a 24-ton ready-mix lorry was used to transport ready-mixed concrete.

j) Most construction activities on the site were done manually, with exception of an excavator for excavation works. A 40-ton low loader was used to transport the excavator in the distance of 50 km.

k) The usage of timber formwork is included during construction and assumed to be transported to landfill later. The formwork is assumed to be used multiple times before disposal, four times for elements in substructures and six times for elements in superstructures as suggested by Abdullah (2005).

l) GQ and PD house energy consumption were estimated as the houses had just completed thus no energy data are available. The energy data were estimated using energy simulation software OpenStudio, which uses EnergyPlus thermal simulation engine (W. J. Cole, Hale, & Edgar, 2013). The Kuala Lumpur weather data for the year 2013 were obtained from US Department of Energy. The following parameters have been considered in the simulation:

- The people definition is set at 0.028309 people/m^2, based on ASHRAE 189.1-2009 Climate Zone 1-3 for Mid-rise Apartment
- The light definition is set at 3.487507 W/m2, based on ASHRAE 189.1-2009 Climate Zone 1-3 for Mid-rise Apartment
- The electrical definition is set at 3.875008 W/m2 based on ASHRAE 189.1-2009 Climate Zone 1-3 for Mid-rise Apartment
- The air conditioning system is set to 20.8º Celcius and working from 10.00pm to 6.00 am every day that reflected the average usage of air-conditioning for residential building based on findings by Kubota, Jeong, Toe, & Ossen (2011)
- The air conditioning system was installed in the master bedroom, and two other bedrooms on the first floor only based on findings by Kubota et al. (2011).
- The energy consumption was assumed constant throughout the operation of the house based on the year 2013.

m) Energy consumptions and generation for EEH were based on actual data provided by the owner. Only solar panel was considered in the LCA and does not include additional equipment such as inverter and wiring.

n) Maintenance data only considered the replacement of selected elements such as painting, replacement of roof coverings and windows as suggested by (Ochsendorf et al., 2011; Ortiz-Rodríguez et al., 2010). The replacement frequencies were estimated based on a report by NAHB (Seiders, Ahluwalia, & Melman, 2007).

o) Demolition and dismantling of these houses are assumed to be done manually. Only transportation to the recycling plant and landfill are considered. The landfill impact is calculated based on Ecoinvent process.

4.3 Case Study 1 – Government quarters (GQ)

4.3.1 *Building Overview*

The government quarter is located in the district of Kuala Selangor, about 70 km from Kuala Lumpur. This semi-detached house has an area of 218 m^2 with five bedrooms, two living rooms, a dining room, a kitchen, utility room and three bathrooms. It is two-storey high, and the primary structure is reinforced concrete with clay bricks as the building envelope.

Figure 4.1: The front view of the GQ

Table 4.1: The quantity of materials used in the construction of GQ

Item	Materials	Qty	Qty/m2 GFA	Unit
A	Substructure			
	Excavation	153.50	0.70	m^3
	Hardcore	18.75	0.09	m^3
	Concrete Grade 7 blinding	8.50	0.04	m^3
	Concrete Grade 30	38.00	0.17	m^3
	Concrete Grade 35	18.50	0.08	m^3
	Reinforcement	6524.83	29.93	kg
	Formwork	5.91	0.03	m^3

Item	Materials	Qty	Qty/m2 GFA	Unit
B	Frame			
	Concrete Grade 30	31.95	0.15	m^3
	Reinforcement Mild Steel	4980.54	22.85	kg
	Formwork	7.46	0.03	m^3
C	Upper Floor			
	Concrete Grade 30	15.59	0.07	m^3
	Reinforcement	1222.54	5.61	kg
	Formwork	1.60	0.01	m^3
D	Stairs			
	Concrete Grade 30	4.50	0.02	m^3
	Reinforcement	375.00	1.72	kg
	Formwork	0.50	0.00	m^3
E	Brickwall			
	Clay brick			
	Half brick thick	474.00	2.17	m^2
	One brick thick	36.50	0.17	m^2
	Concrete block	3.27	0.02	m^2
F	Roof and covering			
	Concrete Grade 30	2.00	0.01	m^3
	Reinforcement	175.18	0.80	kg
	Formwork	0.26	0.00	m^3
	Wall plate	0.0005	0.00	m^3
	Fascia board	0.0003	0.00	m^3
	Painting wood	23.00	0.11	m^2
	Steel Roof Trusses	6812.50	31.25	kg
	Concrete roof coverings	272.50	1.25	m^2
G	Finishes			
	Cement screed	6.98	0.03	m^3
	Ceramic tiles	303.30	1.39	m^2
	Timber strip	53.70	0.25	m^2
	Plasterwork	29.20	0.13	m^3
	Painting	1635.80	7.50	m^2
	Ceiling	170.00	0.78	m^2

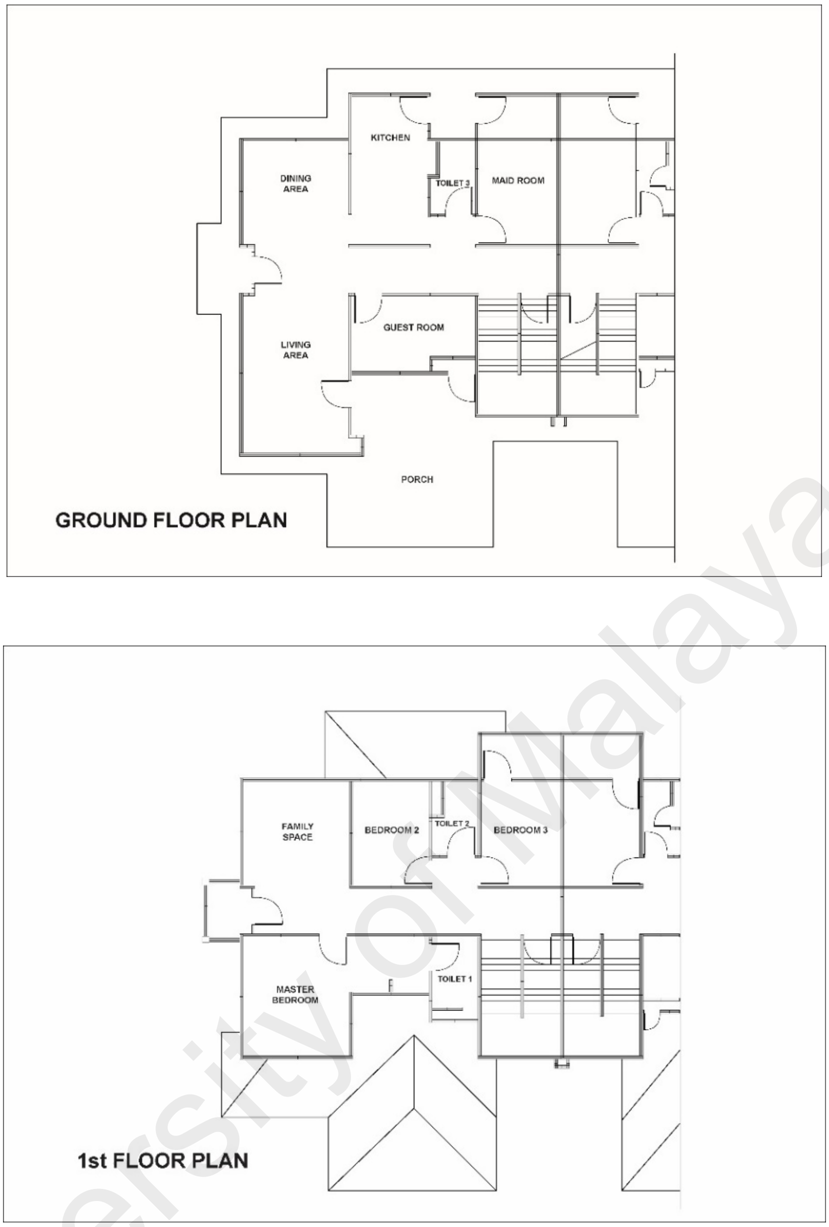


Figure 4.2: GQ's Building layout

4.3.2 *Energy Consumption*

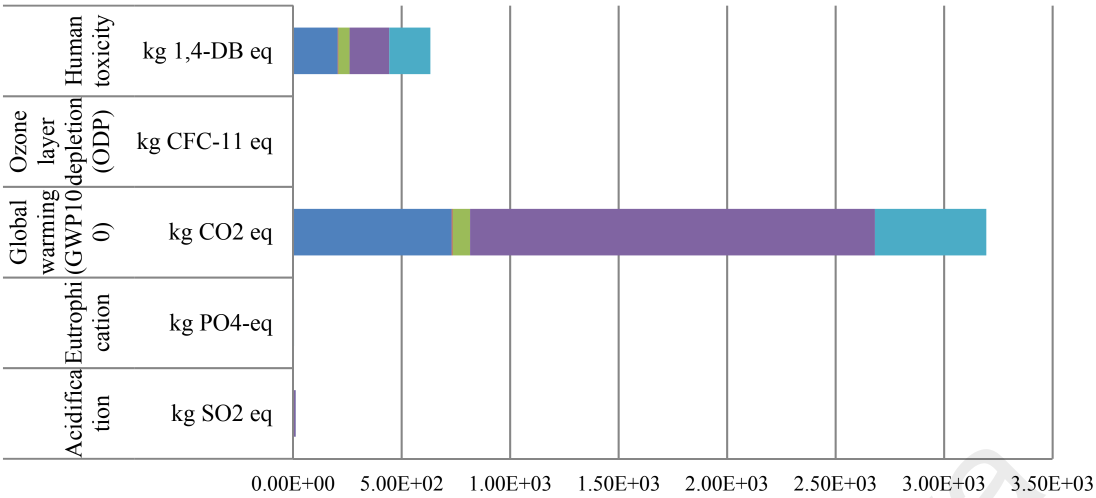
The total energy consumption was simulated for the year 2013 and then multiplied to 50 years for the building lifespan. Since the functional unit of this LCA is 1 m^2 of GFA, the total energy consumption will be divided by 218 m^2 as shown in Table 4.2. The estimated annual consumption per GFA is validated by compared to published data. The simulation result was within an annual average of energy consumption of Malaysian residential buildings which is between 38.31 kWh/m2 to 51.93 kWh/m2 as suggested by (CETDEM, 2006) and (Pomeroy, 2011).

Table 4.2: Result of the simulation for GQ

Annual Energy Consumption (kWh)			
Lighting	**Electrical Equipment**	**Air-conditioning system**	**Total**
1,801.90 (18.13%)	4,011.84 (40.37%)	4,122.48 (41.49%)	9,936.62
Gross Floor Area (GFA) (m^2)	**Annual Energy Consumption per GFA (kWh/m^2)**	**Total Energy Consumption for 50 years (∑kWh)**	**Total Energy Consumption per GFA (∑kWh/m^2)**
218	45.58	496,831.05	2,279.04

4.3.3 *General results*

The life cycle impact assessments (LCIA) for all case studies were based on a functional unit of 1 m^2 of floor area and distributed into five (5) categories which are human toxicity (HT), ozone layer depletion (ODP), global warming potential (GWP), eutrophication and acidification. The results were divided into different phases namely pre-use, construction, maintenance, operations, and EOL. The operation and maintenance phases are part of the use phase category, but they were separated to highlight the different processes in each phase. Figure 4.3 shows the LCIA of GQ according to selected categories with operation phase contributed the highest overall impact especially on GWP (1.87E+03 kg CO_2 eq) and acidification (8.49E+00 kg SO_2 eq) with relatively high HT (1.82E+02 kg 1,4 DB eq) and eutrophication (8.65E-01 kg PO_4-eq).



	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity
	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg 1,4-DB eq
Pre-use	2.73E+00	5.96E-01	7.30E+02	2.36E-05	2.06E+02
Construction	2.51E-02	7.29E-03	4.70E+00	2.92E-07	2.32E+00
Maintenance	4.30E-01	1.42E-01	8.04E+01	8.52E-06	5.23E+01
Operations	8.49E+00	8.65E-01	1.87E+03	1.01E-07	1.82E+02
End of Life	4.85E-01	2.66E+00	5.14E+02	4.52E-06	1.90E+02

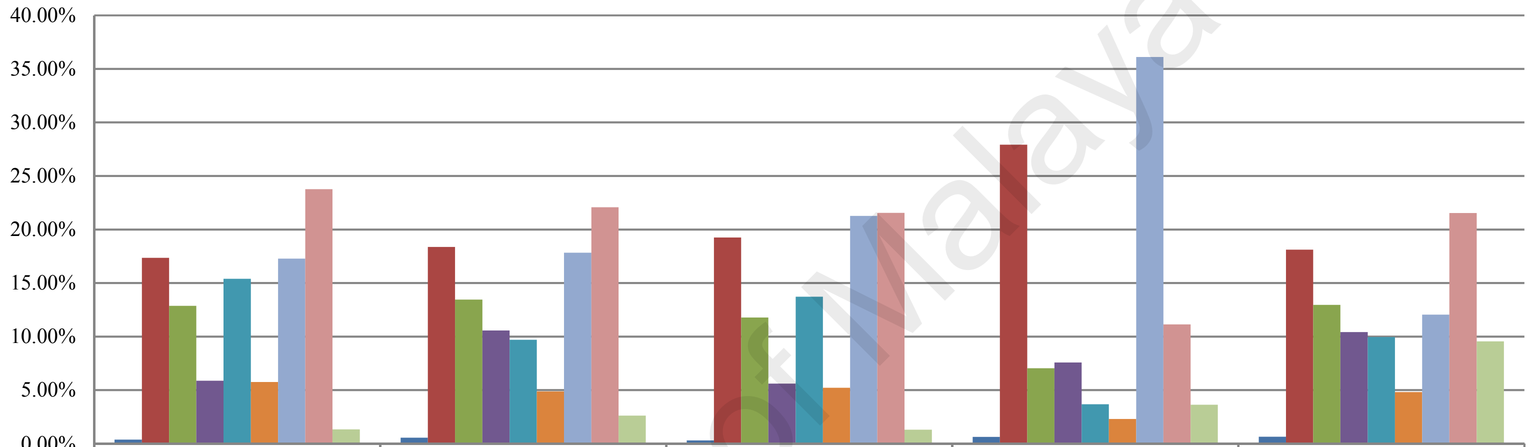
Figure 4.3: LCIA of GQ from cradle-to-grave by using CML 2001

The pre-use phase is the second highest overall impact with the highest impact on ODP with a total impact of 2.36E-05 kg CFC-11 eq in wall and finishes elements. During EOL, the GWP is at 5.14E+02 kg CO_2 eq that is relatively high. The impact is contributed mostly by the disposal of clay brick in wall, ceramic tiles in building finishes and also cement based product such as base plaster and screed to landfill. The maintenance phase is lower than pre-use phase as the building elements that require replacement only limited to roof tiles, painting, and window while the construction phase has the lowest overall impact.

4.3.4 *Results in pre-use phase*

The LCIA of materials used in the building was evaluated from cradle-to-gate i.e. from raw material extraction, manufacturing process, and transportation to the site. Each building elements later converted to the functional unit of 1 m^2 of GFA.

Figure 4.4 shows the LCIA of every element in the GQ. Substructure elements has the highest impact for acidification (6.50E-01 kg SO_2 eq), eutrophication (1.32E-01 kg PO_4-eq), GWP (1.57E+02 kg CO_2 eq) and HT (4.44E+01 kg 1,4-DB eq) excluding for ODP whilst door is the lowest on all impact categories. Cement contribute the highest environmental impact due to high usage of concrete-based building elements such as in substructure, frame, stairs and finishes. Ceramic tiles for finishes including clay bricks for walls have also indicated high environmental impact compare to other elements. The impact of material selections will be discussed further in this chapter.



	kg SO2 eq Acidification	kg PO4- eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Door	0.37%	0.55%	0.30%	0.63%	0.64%
Finishes	17.36%	18.36%	19.25%	27.92%	18.11%
Frame	12.86%	13.45%	11.78%	7.03%	12.96%
Roof & covering	5.87%	10.56%	5.60%	7.57%	10.41%
Stairs	15.40%	9.69%	13.72%	3.68%	9.95%
Upper floor	5.76%	4.87%	5.22%	2.30%	4.81%
Wall	17.28%	17.83%	21.27%	36.11%	12.04%
Substructure	23.77%	22.07%	21.55%	11.13%	21.53%
Window	1.33%	2.61%	1.30%	3.64%	9.54%

Figure 4.4: LCIA of GQ using CML 2001 by building elements in pre-use phase in percentage.

4.3.5 *Results in construction phase*

The construction phase has the lowest environmental impact overall. In the construction phase, three (3) processes were taken into consideration; 1) Excavation process; 2) Transportation of excavator to the construction site with 50 km distance; 3) Formwork for concrete work.

Table 4.3: LCIA of GQ using CML 2001 in construction phase

Environmental Impact	Unit	Total
Acidification	kg SO2 eq	2.51E-02
Eutrophication	kg PO4-eq	7.29E-03
Global warming (GWP100)	kg CO2 eq	4.70E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	2.92E-07
Human toxicity	kg 1,4-DB eq	2.32E+00

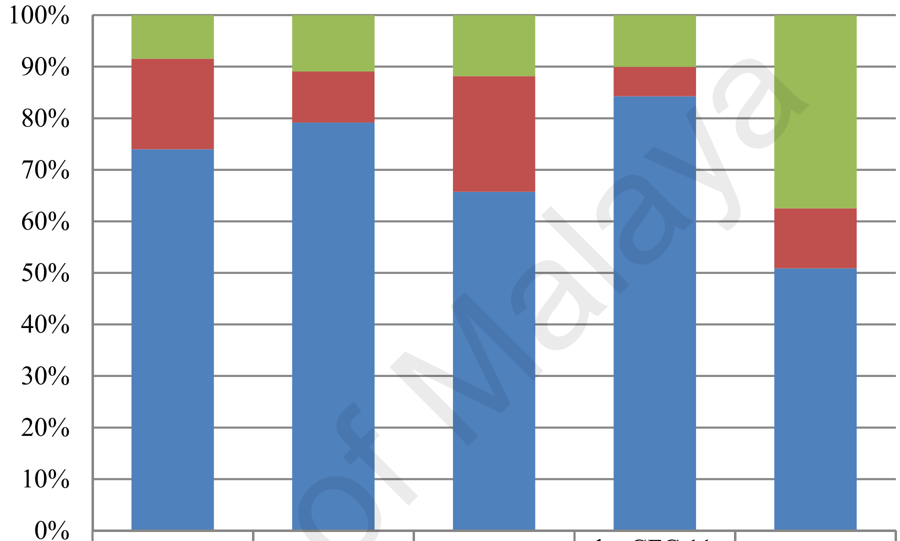
4.3.6 *Results in maintenance phase*

During the maintenance phase, the replacement interval suggested by Seiders, Ahluwalia, & Elman (2007) in NAHB report as guidelines in this research as shown in Table 4.4. The replacement includes the building materials and transportation to the site. The environmental impact of disposal of materials in this phase was also included during EOL.

Table 4.4: Replacement interval of selected building elements in maintenance phase (Seiders et al., 2007)

Elements	Expected Lifespan	Number of replacement in 50 years
Painting	10 years	4 times
Roof covering	25 years	1 times
Window	30 years	1 times

The painting has been identified as the highest environmental impact contributor due to its replacement frequency during building lifespan as shown in Figure 4.5. The impact of a single replacement of paint, however, is still the highest for acidification, eutrophication, ODP, and HT but concrete roof tile has the highest GWP (17.2 kg CO2 eq) compare to a single replacement of painting (12.4 kg CO2 eq).



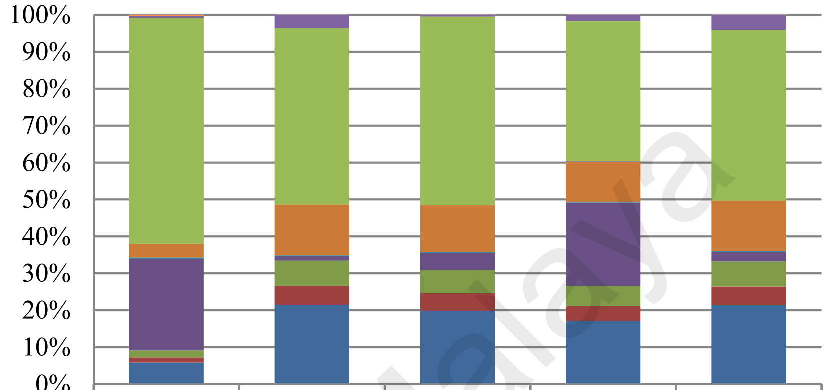
	kg SO2 eq Acidification	kg PO4 eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC 11 eq Ozone layer depletion (ODP)	kg 1,4 DB eq Human toxicity
Aluminium Window	3.64.E-02	1.55.E-02	9.52.E+00	8.58.E-07	1.96.E+01
Concrete Roof Tiles	7.55.E-02	1.41.E-02	1.80.E+01	4.86.E-07	6.09.E+00
Painting	3.18.E-01	1.12.E-01	5.28.E+01	7.18.E-06	2.66.E+01

Figure 4.5: LCIA of GQ using CML 2001 by building elements in the maintenance phase.

4.3.7 *Results in EOL phase*

The process included in the EOL is the transportation of demolition debris to landfill located 50 km from building site and also the impact of disposal of building materials in the landfill. The environmental impact during this phase is the third highest overall with the highest level of eutrophication (2.66E+00 kg PO_4-eq) with relatively high GWP

(5.14E+02 kg CO_2 eq), acidification (4.85E+00 kg SO_2 eq) and HT (1.90E+02 kg 1,4-DB eq). Figure 4.6 shows the total environmental impact of transportation and disposal of building materials in the landfill. The impact of disposal of bricks is the highest in all impact categories followed by cement based products.



	kg SO2 eq Acidificatio n	kg PO4--- eq Eutrophicat ion	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Window Aluminium Frame Single Glaze	6.25E-06	1.51E-06	1.12E-03	1.72E-10	2.68E-04
Timber Floor Strip	1.47E-03	3.51E-04	2.82E-01	6.20E-10	1.06E-02
Timber Product	1.16E-07	3.11E-08	2.27E-05	9.82E-13	4.68E-06
Painting	2.75E-03	9.62E-02	2.28E+00	7.44E-08	7.82E+00
Clay Bricks	2.96E-01	1.27E+00	2.62E+02	1.72E-06	8.76E+01
Formwork	5.87E-05	1.58E-05	1.15E-02	4.98E-10	2.37E-03
Door	9.71E-08	2.61E-08	1.90E-05	8.24E-13	3.93E-06
Concrete Roof Tiles	1.81E-02	3.66E-01	6.54E+01	4.96E-07	2.59E+01
Concrete Hollow Block	1.97E-03	5.41E-03	1.22E+00	7.40E-09	3.66E-01
Concrete	1.20E-01	3.23E-02	2.36E+01	1.02E-06	4.86E+00
Ceramic Tiles	9.03E-03	1.82E-01	3.26E+01	2.47E-07	1.29E+01
Cement Screed	6.72E-03	1.36E-01	2.42E+01	1.84E-07	9.62E+00
Baseplaster	2.82E-02	5.71E-01	1.02E+02	7.73E-07	4.04E+01

Figure 4.6: LCIA of EOL of GQ using CML 2001 by building materials

4.4 Case Study 2 – Private Developer's house (PD)

4.4.1 *Building Overview*

This residential project is located in the district of Seri Kembangan, about 25 km from Kuala Lumpur. This semi-detached house has an area of 246 m^2 with five bedrooms, one living room, a dining room, a dry kitchen, a wet kitchen, a family area, a study area and five bathrooms. Similar to the GQ, it is a two-storey high, and the main structure is reinforced concrete with clay bricks as the building envelope.

Table 4.5: The quantity of materials used in the construction of the private developer

Item	Materials	Quantity	Qty/m2 GFA	Unit
A	Substructure			
	Excavation	86.02	0.35	m^3
	Hardcore	15.44	0.06	m^3
	Concrete Grade 7 blinding	21.74	0.09	m^3
	Concrete Grade 25	184.03	0.75	m^3
	Reinforcement	2,561.62	10.41	kg
	Formwork	4.13	0.02	m^3
B	Frame			
	Concrete Grade 25	23.2	0.09	m^3
	Reinforcement	3883	15.78	kg
	Formwork	7.69	0.03	m^3
C	Upper Floor			
	Concrete Grade 25	28.73	0.12	m^3
	Reinforcement	1709.62	6.95	kg
	Formwork	3.35	0.01	m^3
D	Stairs			
	Concrete Grade 25	2.78	0.01	m^3
	Reinforcement	243	0.99	kg
	Formwork	1.07	0.01	m^3
E	Brickwall			
	Clay brick			
	Half brick thick	381	1.55	m^2
	One brick thick	37.14	0.15	m^2

Item	Materials	Quantity	Qty/m2 GFA	Unit
F	Roof and covering			
	Fascia board	0.31	0.00	m^3
	Painting wood	21.61	0.09	m^2
	Timber Roof Trusses	10.65	0.04	m^3
	Clay roof coverings	213.84	0.87	m^2
G	Finishes			
	Cement screed	9.47	0.04	m^3
	Ceramic tiles	357.59	1.45	m^2
	Timber strip	116.09	0.47	m^2
	Plasterwork	18.57	0.08	m^3
	Painting	1229.5	5.00	m^2
	Ceiling	174.93	0.71	m^2

Figure 4.7: The overview of the project

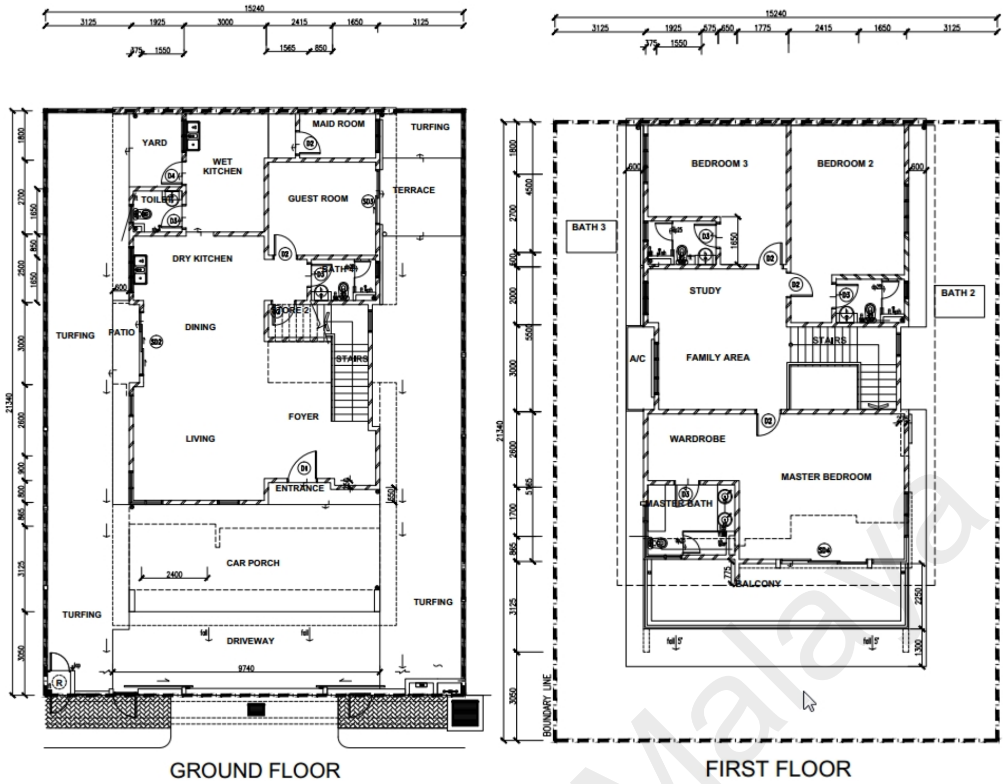


Figure 4.8: PD's Building layout

4.4.2 *Energy Consumption*

The total energy consumption was simulated for the year 2013 and then multiplied to 50 years for the building lifespan. As the functional unit of this LCA is 1 m^2 of GFA, the total energy consumption will be divided by 246 m^2 as shown in Table 4.6. The estimated annual consumption per GFA is slightly higher than the annual average of energy consumption of Malaysian residential buildings as suggested by (CETDEM, 2006) and (Pomeroy, 2011).

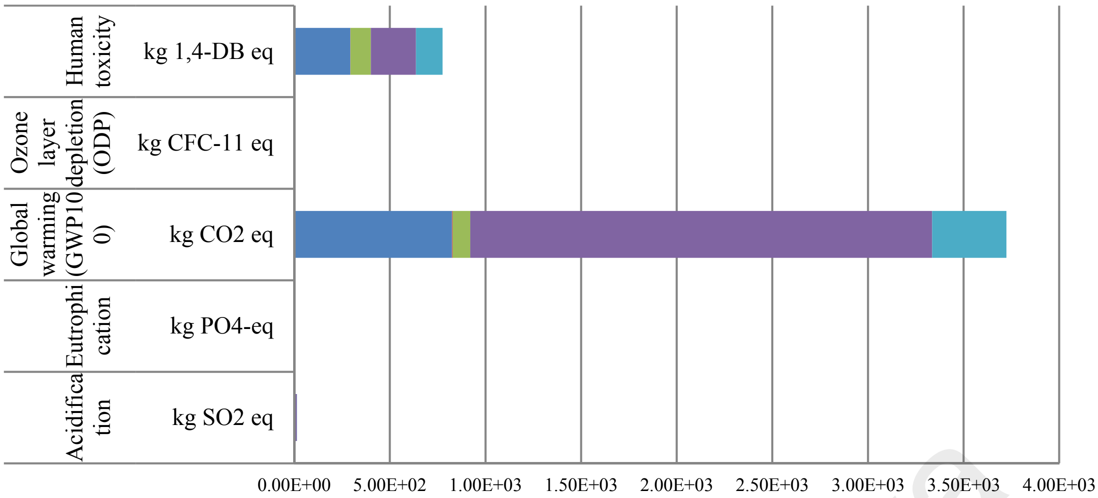
Table 4.6: Result of the simulation for PD

Annual Energy Consumption (kWh)			
Lighting	**Electrical Equipment**	**Air-conditioning system**	**Total**
2,382.85 (16.42%)	5,305.32 (36.56%)	6,824.73 (47.03%)	14,512.00
Gross Floor Area (GFA) (m2)	**Annual Energy Consumption per GFA (kWh/m2)**	**Energy Consumption for 50 years (∑kWh)**	**Total Energy Consumption per GFA (∑kWh/m2)**
246	59.00	725,644.95	2,949.78

4.4.3 *General results*

Figure 4.9 shows the total environmental impact for PD according to selected categories. Similar to GQ, operation phase contributed the highest overall impact especially on GWP (2.14E+03 kg CO_2 eq) and acidification (1.10E+00 kg SO_2 eq) with relatively high HT (2.36E+02 kg 1,4 DB eq) and eutrophication (1.12E-01 kg PO_4-eq).

The pre-use phase is the second highest overall impact with the highest impact on ODP with a total impact of 2.39E-05 kg CFC-11 eq. EOL has been identified as the third highest impact especially on GWP (3.89E+02 kg CO_2 eq) which is relatively high. Similar to GQ, the impact is contributed mostly by the disposal of clay brick in building wall, ceramic tiles in building finishes and also cement based product such as base plaster and screed to landfill. Maintenance phase impact is lower than a pre-use phase, and the construction phase has the lowest overall impact.

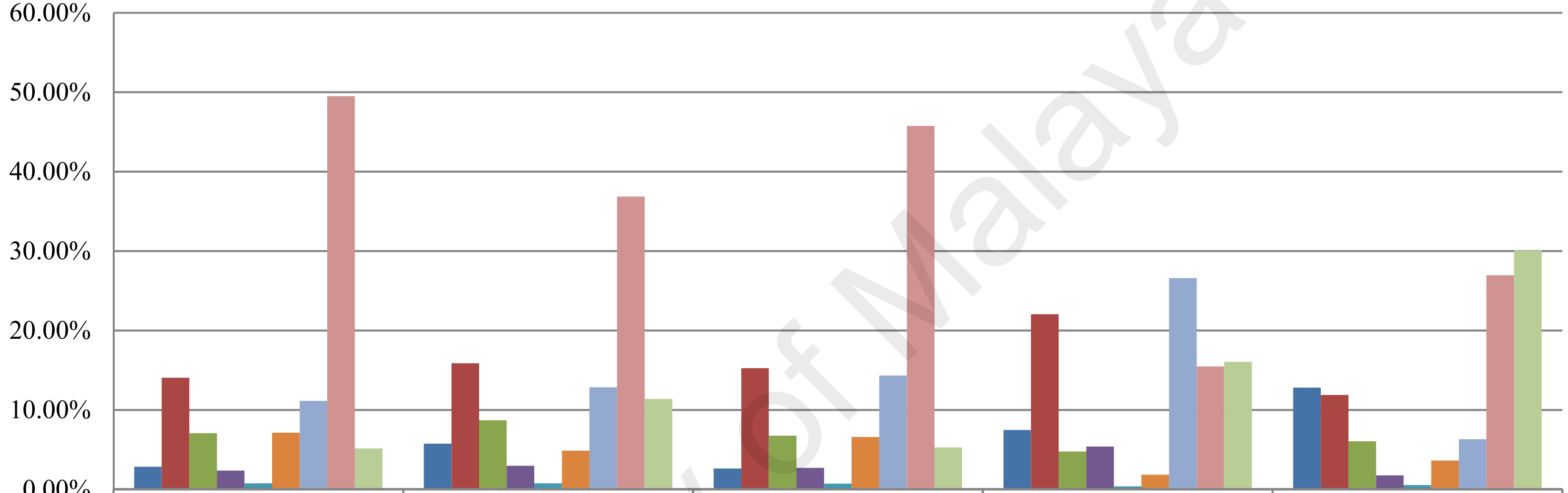


	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity
	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg 1,4-DB eq
Pre-use	3.23E+00	6.19E-01	8.25E+02	2.39E-05	2.94E+02
Construction	1.74E-02	5.04E-03	3.29E+00	2.03E-07	1.56E+00
Maintenance	4.09E-01	1.49E-01	9.19E+01	9.42E-06	1.06E+02
Operations	1.10E+01	1.12E+00	2.41E+03	1.31E-07	2.36E+02
End of Life	4.62E-01	1.92E+00	3.89E+02	4.05E-06	1.39E+02

Figure 4.9: LCIA of PD from cradle-to-grave by using CML 2001

4.4.4 *Results in pre-use phase*

Figure 4.10 shows the environmental impact of every element in the PD. Substructure elements has the highest impact for acidification (1.60E+00 kg SO_2 eq), eutrophication (2.28E-01 kg PO_4-eq), and GWP (3.77E+02 kg CO_2 eq). Windows has the highest HT (8.84E+01 kg 1,4-DB eq). Stair has the lowest overall impact, unlike GQ, which is door. Similar results were found where cement contributed the highest environmental impact due to high usage of concrete-based building elements. Ceramic tiles for finishes and clay bricks for walls have also indicated high environmental impact compare to other elements.



	kg SO2 eq Acidification	kg PO4- eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Door	2.84%	5.75%	2.63%	7.47%	12.80%
Finishes	14.04%	15.87%	15.25%	22.05%	11.89%
Frame	7.07%	8.69%	6.76%	4.76%	6.05%
Roof & covering	2.35%	2.96%	2.70%	5.38%	1.75%
Stairs	0.75%	0.76%	0.71%	0.38%	0.54%
Upper floor	7.14%	4.87%	6.60%	1.85%	3.63%
Wall	11.15%	12.85%	14.33%	26.59%	6.31%
Substructure	49.50%	36.86%	45.75%	15.47%	26.95%
Window	5.15%	11.39%	5.27%	16.05%	30.08%

Figure 4.10: LCIA of PD using CML 2001 by building elements in pre-use phase in percentage.

4.4.5 *Results in construction phase*

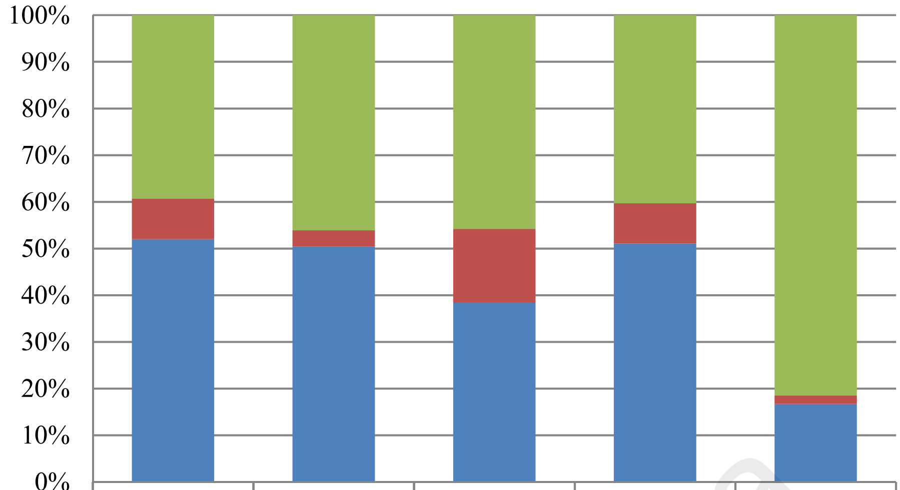
The construction phase produces similar results as GQ where it has the lowest environmental impact.

Table 4.7: LCIA of PD using CML 2001 in construction phase

Impact category	Unit	Total
Acidification	kg SO2 eq	1.74E-02
Eutrophication	kg PO4-eq	5.04E-03
Global warming (GWP100)	kg CO2 eq	3.29E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	2.03E-07
Human toxicity	kg 1,4-DB eq	1.56E+00

4.4.6 *Results in maintenance phase*

In PD, painting and aluminium frame window has been identified the two highest environmental impact contributors. Painting has the highest impact on acidification (2.08E-01 kg SO_2 eq), eutrophication (7.36E-02 kg PO_4-eq) and ODP (4.68E-06 kg CFC-11 eq). Aluminium frame window has the highest impact on GWP (4.21E+01 kg CO_2 eq) and HT (8.66E+01 kg 1,4-DB eq) as shown in Figure 4.11. PD has a larger quantity of aluminium windows in comparison to GQ, which increases the environmental impact of windows. Unlike GQ, PD uses clay roof tiles rather than concrete roof tiles which produce slightly lower overall environmental impact in acidification, eutrophication, and HT but higher in GWP and ODP, which will be discussed further in this chapter.

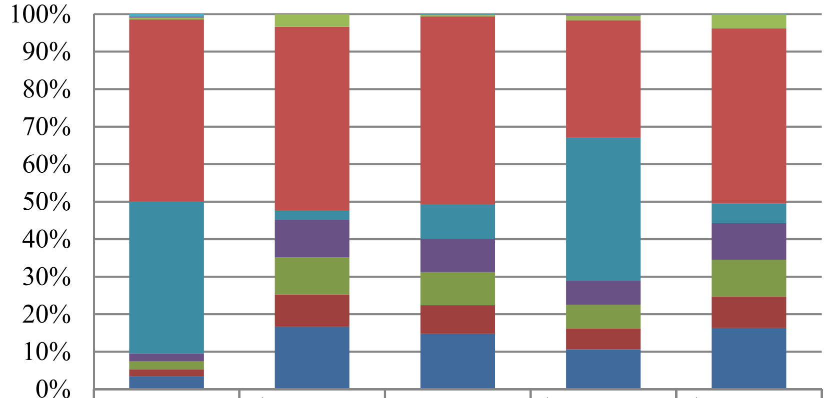


	kg SO2 eq Acidification	kg PO4 eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC 11 eq Ozone layer depletion (ODP)	kg 1,4 DB eq Human toxicity
Aluminium Window	1.61.E-01	6.88.E-02	4.21.E+01	3.79.E-06	8.66.E+01
Clay Roof Tiles	3.54.E-02	5.20.E-03	1.46.E+01	8.13.E-07	1.87.E+00
Painting	2.13.E-01	7.52.E-02	3.53.E+01	4.81.E-06	1.78.E+01

Figure 4.11: LCIA of PD using CML 2001 by building elements in the maintenance phase.

4.4.7 *Results in EOL phase*

Similar to GQ, the environmental impact during this phase is the third highest overall with the highest level of eutrophication (1.92E+00 kg PO_4-eq) with relatively high GWP (3.89E+03 kg CO_2 eq). Figure 4.12 shows the total environmental impact of transportation and disposal of building materials in the landfill. The impact of disposal of bricks is the highest in all impact categories followed by cement based products i.e. concrete, base plaster, and screed.



	kg SO2 eq Acidification	kg PO4--- eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Window Aluminium Frame Single Glaze	2.76E-05	6.67E-06	4.95E-03	7.60E-10	1.18E-03
Timber Floor Strip	2.82E-03	6.73E-04	5.41E-01	1.19E-09	2.04E-02
Timber Product	1.71E-03	4.59E-04	3.35E-01	1.45E-08	6.91E-02
Painting	1.84E-03	6.43E-02	1.52E+00	4.97E-08	5.22E+00
Clay Bricks	2.19E-01	9.38E-01	1.93E+02	1.27E-06	6.47E+01
Formwork	4.09E-05	1.10E-05	8.03E-03	3.47E-10	1.66E-03
Door	5.24E-06	1.27E-06	9.41E-04	1.39E-10	2.24E-04
Concrete	1.82E-01	4.90E-02	3.57E+01	1.55E-06	7.37E+00
Clay Roof Tiles	9.60E-03	1.91E-01	3.42E+01	2.60E-07	1.35E+01
Ceramic Tiles	9.43E-03	1.91E-01	3.40E+01	2.58E-07	1.35E+01
Cement Screed	8.18E-03	1.66E-01	2.96E+01	2.24E-07	1.17E+01
Baseplaster	1.58E-02	3.20E-01	5.71E+01	4.32E-07	2.26E+01

Figure 4.12: LCIA of EOL of PD using CML 2001 by building materials

4.5 Case Study 3 – Energy Efficient House (EEH)

4.5.1 *Building Overview*

This residential building is located in the district Ayer Keroh in Melaka, about 135km from Kuala Lumpur. This detached house has an area of 232m^2 with two bedrooms, a living room, a study room, a kitchen a store, a garage and work room and two bathrooms. The building is specifically designed by the owner, focusing on energy efficiency.

Unlike the other two buildings that use reinforced concrete structure, the superstructure for this house is load bearing walls. Load bearing walls is a system where it uses walls to transfer the load to the foundation rather than column and beams. The bricks are aerated concrete blocks which are lighter than a standard block with similar size. The following are the energy efficiency feature of this EEH:

- The building orientation and windows are facing North to prevent direct sunlight.
- The windows and external doors are double glazed with argon gas in between to prevent heat transfer.
- External walls built using aerated concrete blocks that provide insulation and painted white to reflect heat.
- Insulation materials above the ceiling to stop overhead radiating down; insulation materials below the floor to stop cold air from seeping to earth.
- Special ventilation from outside and warm air ejected using the thermal chimney.
- Overhang roof with white zinc aluminium coated steel.
- The location is within natural shades, much cooler than conventional housing projects.
- Energy efficient appliances and lightings with 24-hours air conditioning.

Due to its innovative design and efficiency, EEH has been awarded ASEAN Energy Award in 2009 (Boswell & Bacon, 2009). However when EEH was evaluated to the 'Malaysian Green Building Index for New Residential Construction' (GBI-RNC) format, it does not achieved the minimum point to be GBI certified due to its remote location, which does not score enough in 'Sustainable Site Planning and Management' indicator (Muhammad Azzam & Fahanim, 2011).

Table 4.8: The quantity of materials used in the construction of EEH

Item	Materials	Quantity	Qty/m2 GFA	Unit
A	Substructure			
	Excavation	64.00	0.28	m^3
	Hardcore	124.00	0.53	m^3
	Concrete Grade 7 blinding	8.08	0.03	m^3
	Concrete Grade 30	38.40	0.17	m^3
	Reinforcement	4369.60	18.83	kg
	Formwork	1.87	0.01	m^3
B	Brickwall			
	Aerated autoclaved concrete block			
	Half brick thick	116.28	0.50	m^2
	One brick thick	189.72	0.82	m^2
C	Roof and covering			
	Lightweight Steel Roof Trusses	6135.00	26.44	kg
	Rockwool	409.00	1.76	m^2
	Aluminium Roof Cladding	409.00	1.76	m^3
D	Finishes			
	Cement screed	4.00	0.02	m^3
	Ceramic tiles	100.00	0.43	m^2
	Timber strip	132.00	0.57	m^2
	Plasterwork	4.26	0.02	m^3
	Painting	737.00	3.18	m^2
	Insulation	132.00	0.57	m^2

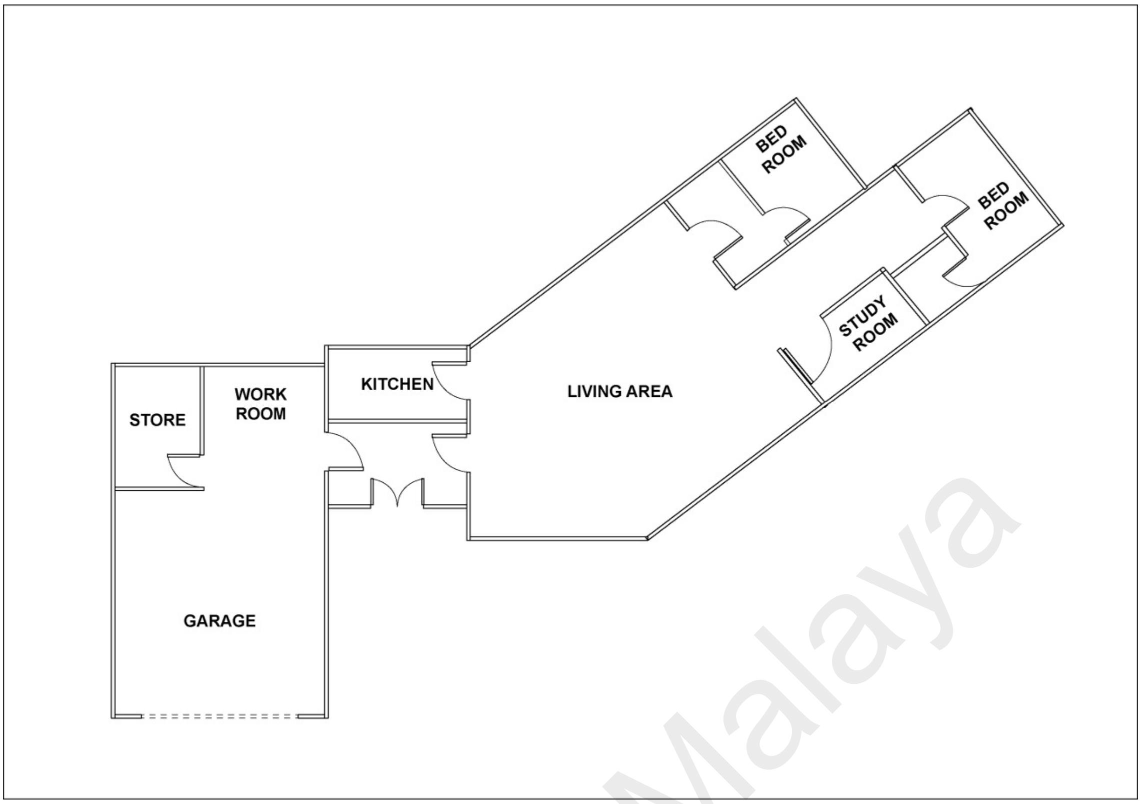


Figure 4.13: EEH Building layout

4.5.2 *Energy Consumption*

The total energy consumption was furnished by the owner of the EEH. The average energy data were calculated based on data collected from November 2007 to July 2012. The average then multiplied to 50 years for the building lifespan. As the functional unit of this LCA is $1m^2$ of GFA, the total energy consumption will be divided by $232m^2$ of floor area shown in Table 4.9. The EEH also equipped with forty (40) 120-watt polycrystalline solar panels on the roof with 4.8 kW peak. The data for electricity generated from the solar panel were recorded during the same period as above. The average generated electricity was calculated based on the data collected, divided by functional unit and multiplied to 50 years as shown in Table 4.9.

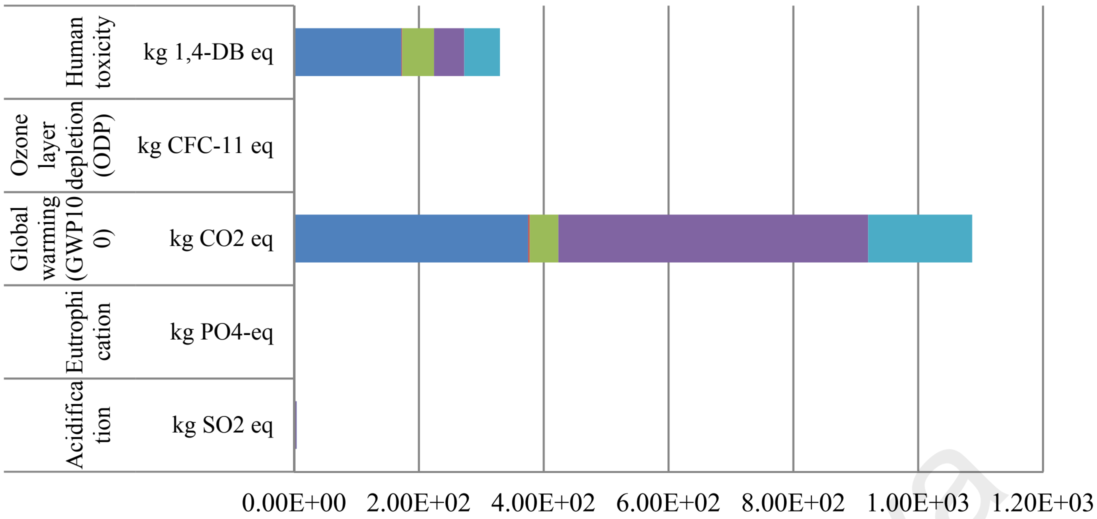
Table 4.9: Result from actual data for EEH

Average Energy Consumption (kWh)			
Lighting	**Electrical Equipment**	**Air-conditioning system**	**Total**
88.86 (1.03%)	3,605.98 (41.80%)	4,931.05 (57.16%)	8,626.75
Gross Floor Area (GFA) (m2)	**Average Energy Consumption per year per GFA (kWh/m2)**	**Total Energy Consumption for 50 years (∑kWh)**	**Total Energy Consumption per GFA (∑kWh/m2)**
232	37.18	431,337.50	1,859.21
Average Energy Generated (kWh)	**Average Energy Generated per GFA (kWh/m2)**	**Total Energy Generated for 50 years (∑kWh)**	**Total Energy Generated per GFA (∑kWh/m2)**
5,814.94	25.06	290,746.98	1,253.22

4.5.3 *General results*

Figure 4.14 shows the total environmental impact for EEH according to selected categories. Unlike GQ and PD, operation phase in EEH overall impact is somewhat comparable to its pre-use phase. The operation phase only has the highest environmental impact in acidification (2.26E+00 kg SO_2 eq) and GWP (4.96E+02 kg CO_2 eq). The pre-use phase has the highest ODP (2.05E-05 kg CFC-11 eq) and HT (1.72E+02 kg 1,4-DB eq) while at the same time has the second highest impact on eutrophication (4.18E-01 kg PO_4-eq) and GWP (3.75E+02 kg CO_2 eq).

During EOL, the EEH has the highest impact on eutrophication (8.22E-01 kg PO_4-eq) while also has a relatively high GWP (1.67E+02 kg CO_2 eq) and HT (5.73E+01 kg CO2 eq). Similar to GQ and PD, the high impact is contributed mostly by the disposal brick in building wall but for EEH it is AAC brick rather than clay brick. Similar to previous case studies, maintenance phase is lower than a pre-use phase, and the construction phase has the lowest overall impact.

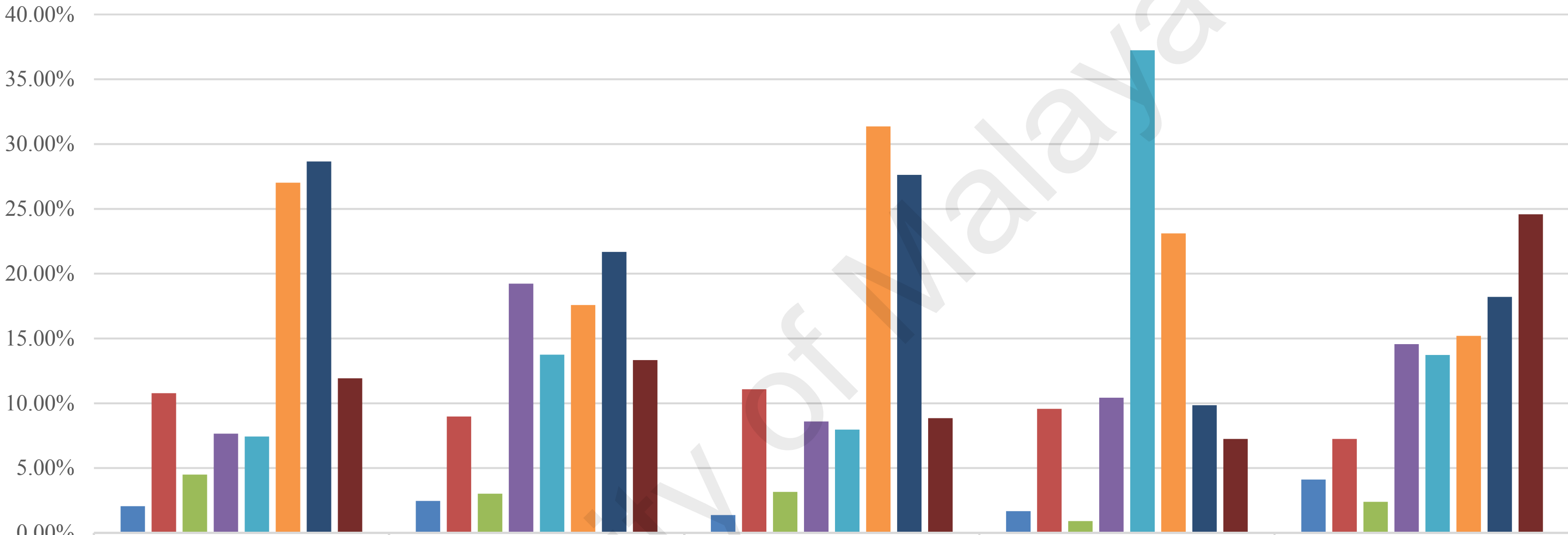


	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity
	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg 1,4-DB eq
Pre-use	1.51E+00	4.18E-01	3.75E+02	2.05E-05	1.72E+02
Construction	1.16E-02	3.44E-03	2.45E+00	1.33E-07	1.13E+00
Maintenance	2.41E-01	8.57E-02	4.61E+01	2.72E-06	5.10E+01
Operations	2.26E+00	2.30E-01	4.96E+02	2.70E-08	4.85E+01
End of Life	2.10E-01	8.22E-01	1.67E+02	1.40E-06	5.73E+01

Figure 4.14: LCIA of EEH from cradle-to-grave by using CML 2001

4.5.4 *Results in pre-use phase*

Figure 4.15 shows the environmental impact of every element in the PD. Substructure element has the highest impact for acidification (4.22E-01 kg SO_2 eq) and eutrophication (8.56E-01 kg PO_4-eq). Wall has the highest GWP impact (1.25E+02 kg CO_2 eq) due to the AAC concrete block used which is based on cement. The solar panels have the highest impact on ODP (6.84E-06 kg CFC-11 eq), and double glazed PVC windows is the highest on HT (4.14E+01 kg 1,4-DB eq). Doors and insulation elements have the lowest overall impact. Similar results were found where cement contributed the highest environmental impact due to high usage of concrete-based building elements.



	kg SO2 eq Acidification	kg PO4- eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Door	2.05%	2.46%	1.38%	1.68%	4.11%
Finishes	10.77%	8.97%	11.08%	9.56%	7.24%
Insulation	4.50%	3.02%	3.16%	0.91%	2.40%
Roof & Covering	7.65%	19.23%	8.60%	10.43%	14.56%
Solar panel	7.43%	13.74%	7.97%	37.23%	13.72%
Wall	27.02%	17.57%	31.35%	23.11%	15.20%
Substructure	28.66%	21.67%	27.62%	9.84%	18.20%
Window	11.93%	13.33%	8.85%	7.24%	24.58%

Figure 4.15: LCIA of EEH using CML 2001 by building elements in pre-use phase in percentage.

4.5.5 *Results in construction phase*

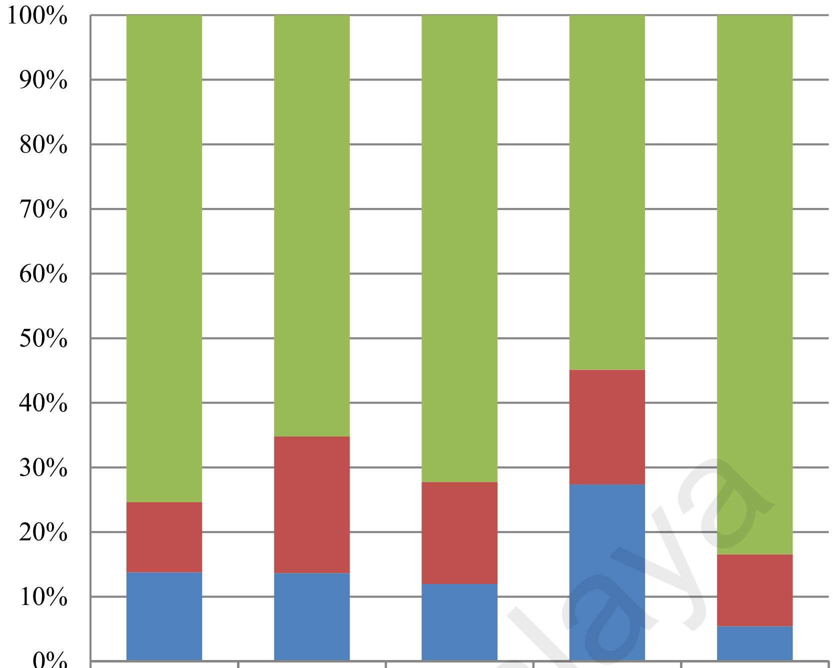
The construction phase produces similar results as GQ and PD where it has the lowest environmental impact.

Table 4.10: LCIA of EEH using CML 2001 in construction phase

Impact category	Unit	Total
Acidification	kg SO_2 eq	1.16E-02
Eutrophication	kg PO_4- eq	3.44E-03
Global warming (GWP100)	kg CO_2 eq	2.45E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1.33E-07
Human toxicity	kg 1,4-DB eq	1.13E+00

4.5.6 *Results in maintenance phase*

In EEH, PVC frame double glazed windows has been identified as the highest environmental impact contributor on all categories; acidification (1.73E-01 kg SO_2 eq), eutrophication (5.32E-02 kg PO_4-eq), GWP (3.17E+01 kg CO_2 eq), ODP (1.42E-06 kg CFC-11 eq) and HT (8.66E+01 kg 1,4-DB eq). Unlike GQ and PD, EEH uses steel roof coverings that produce lowest environmental impact in acidification and ODP due to the recycling potential. The painting also scores lower in all impact categories compare to PVC window frame especially on eutrophication, GWP, and HT.

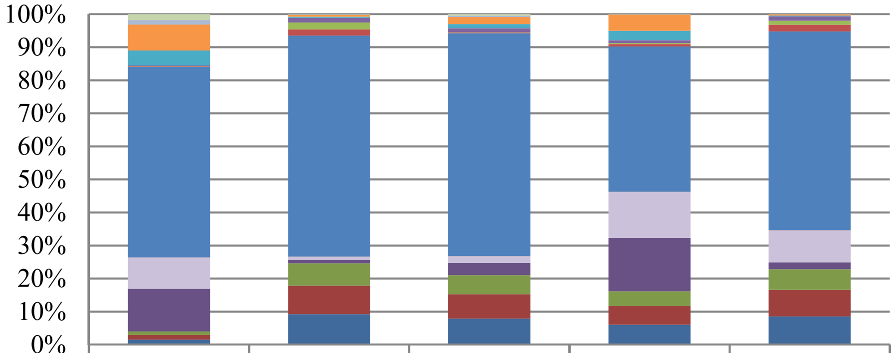


	kg SO2 eq Acidification	kg PO4 eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC 11 eq Ozone layer depletion (ODP)	kg 1,4 DB eq Human toxicity
Aluminium Window	1.81.E-01	5.59.E-02	3.33.E+01	1.49.E-06	4.25.E+01
Clay Roof Tiles	2.62.E-02	1.81.E-02	7.27.E+00	4.83.E-07	5.66.E+00
Painting	3.31.E-02	1.17.E-02	5.51.E+00	7.44.E-07	2.77.E+00

Figure 4.16: LCIA of EEH using CML 2001 by building elements in the maintenance phase.

4.5.7 *Results in EOL phase*

Similar to GQ and PD, the environmental impact during this phase is the third highest overall with the highest level of eutrophication (8.22E-01 kg PO_4-eq) with relatively high GWP (1.67E+02 kg CO_2 eq). Figure 4.17 shows the total environmental impact of transportation and disposal of building materials in the landfill. The impact of disposal of autoclaved aerated concrete (AAC) bricks is identified as the highest in all impact categories.



	kg SO2 eq Acidification	kg PO4--- eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Solar Panel	4.63E-03	1.10E-03	8.87E-01	1.95E-09	3.34E-02
Window	1.38E-05	3.28E-06	2.64E-03	5.80E-12	9.94E-05
Timber Floor Strip	3.41E-03	8.11E-04	6.52E-01	1.43E-09	2.46E-02
Steel Roof Trusses	1.99E-02	4.74E-03	3.77E+00	8.39E-08	2.43E-01
Steel Roof Covering	1.15E-02	2.75E-03	2.19E+00	4.87E-08	1.41E-01
Rockwool Insulation	5.61E-04	1.18E-02	2.11E+00	1.58E-08	8.36E-01
PU Insulation	1.16E-04	1.73E-02	1.18E-01	4.32E-09	7.70E-01
Painting	4.59E-04	1.61E-02	3.80E-01	1.24E-08	1.31E+00
ACC Block	1.46E-01	5.58E-01	1.17E+02	7.57E-07	3.83E+01
Formwork	6.59E-06	1.77E-06	1.29E-03	5.59E-11	2.66E-04
Door	2.40E-02	8.03E-03	3.63E+00	2.41E-07	6.19E+00
Concrete	3.27E-02	8.79E-03	6.41E+00	2.78E-07	1.32E+00
Ceramic Tiles	2.80E-03	5.65E-02	1.01E+01	7.65E-08	4.00E+00
Cement Screed	3.57E-03	7.21E-02	1.29E+01	9.76E-08	5.11E+00
Baseplaster	3.79E-03	7.67E-02	1.37E+01	1.04E-07	5.43E+00

Figure 4.17: LCIA of EOL of EEH using CML 2001 by building materials

4.6 Discussion on Overall Results

4.6.1 *Building Overview*

The three case study buildings have different gross floor area which are 218 m^2 (GQ), 246 m^2 (PD) and 232 m^2 (EEH). The material specification and design for GQ and PD is somewhat comparable and represent the conventional residential building construction in Malaysia. EEH alternatively is almost entirely different, because it was designed towards energy efficiency. The annual energy consumption estimated from the simulations showed the PD consume more due to the larger gross floor area. The estimated annual energy consumption per m^2 for GQ and PD area are 45.58 kWh/m^2 and 59.00 kWh/m^2 respectively. The actual average of energy consumption per m^2 for EEH is 37.18 kWh/m^2 while the average energy generated is 25.06 kWh/m^2. The higher the energy consumed, the higher LCIA in the operation phase.

The results of overall LCIA of GQ, PD, and EEH are shown in Table 4.11 and Figure 4.18. A similar pattern can be seen in all buildings where the operation phase has dominated the LCIA on acidification (53-73%) and GWP (46-65%). The pre-use phase has the highest impact of ODP (64-83%) and HT (33-52%) while the EOL has the highest impact of eutrophication (50-62%).

PD has been identified as the highest impact during pre-use, maintenance and operation phases, while GQ has the highest impact on construction and EOL phases. EEH is the lowest of all categories and in all building phases. The pre-use phase in PD has the highest due to the higher concrete volume in the substructure work compared to other buildings. GQ has the highest impact on construction mainly contributed by the larger excavation works involved. The maintenance phase in PD shows the highest impact on almost all categories contributed by higher quantities for aluminium windows. However, the acidification is the highest in GQ due to larger painting area.

The higher impact of EOL mainly contributed by clay bricks and a higher grade of concrete in comparison to other case studies. Table 4.12 shows the quantities for disposal scenario of all three (3) buildings. The quantities for GQ are higher in cement-based product such as base plaster, concrete block, concrete, concrete roof tiles and also the quantities for clay bricks. These two (2) based products i.e. cement and clay show high disposal impact as shown and discussed earlier in Figure 4.6, Figure 4.12, Figure 4.17.

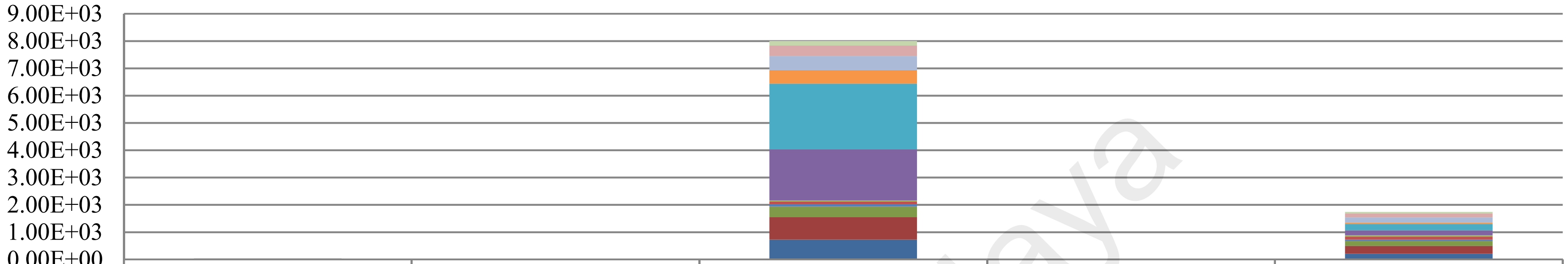
4.6.2 *Normalisation of Results*

In this research, these values in normalisation references are of World data in 1995 as global normalisation references is recommended as default (Dreyer, Niemann, & Hauschild, 2003).

Figure 4.19 shows the normalised results of GQ, PD, and EEH The results show that every building has the largest contributions of GWP during pre-use, construction, maintenance, and operations phase followed by acidification which conforms with results in other research (Szalay, 2007). Eutrophication has the highest impact during EOL phase, similar to other research (Szalay, 2007).

Table 4.11: Summary of LCIA of all case studies using CML 2001

Building	Impact category	Unit	Total	Pre-use	%	Construction	%	Maintenance	%	Operations	%	End of Life	%
GQ	Acidification	kg SO2 eq	1.22E+01	2.73E+00	22.5%	2.51E-02	0.2%	4.30E-01	3.5%	8.49E+00	69.8%	4.85E-01	4.0%
	Eutrophication	kg PO4-eq	4.27E+00	5.96E-01	13.9%	7.29E-03	0.2%	1.42E-01	3.3%	8.65E-01	20.3%	2.66E+00	62.3%
	GWP	kg CO2 eq	3.19E+03	7.30E+02	22.9%	4.70E+00	0.1%	8.04E+01	2.5%	1.87E+03	58.4%	5.14E+02	16.1%
	ODP	kg CFC-11 eq	3.70E-05	2.36E-05	63.7%	2.92E-07	0.8%	8.52E-06	23.0%	1.01E-07	0.3%	4.52E-06	12.2%
	HT	kg 1,4-DB eq	6.32E+02	2.06E+02	32.6%	2.32E+00	0.4%	5.23E+01	8.3%	1.82E+02	28.8%	1.90E+02	30.0%
PD	Acidification	kg SO2 eq	1.51E+01	3.23E+00	21.4%	1.74E-02	0.1%	4.09E-01	2.7%	1.10E+01	72.7%	4.62E-01	3.1%
	Eutrophication	kg PO4-eq	3.82E+00	6.19E-01	16.2%	5.04E-03	0.1%	1.49E-01	3.9%	1.12E+00	29.3%	1.92E+00	50.4%
	GWP	kg CO2 eq	3.72E+03	8.25E+02	22.2%	3.29E+00	0.1%	9.19E+01	2.5%	2.41E+03	64.8%	3.89E+02	10.4%
	ODP	kg CFC-11 eq	3.77E-05	2.39E-05	63.4%	2.03E-07	0.5%	9.42E-06	25.0%	1.31E-07	0.3%	4.05E-06	10.8%
	HT	kg 1,4-DB eq	7.76E+02	2.94E+02	37.8%	1.56E+00	0.2%	1.06E+02	13.7%	2.36E+02	30.4%	1.39E+02	17.9%
EEH	Acidification	kg SO2 eq	4.23E+00	1.51E+00	35.8%	1.16E-02	0.3%	2.41E-01	5.7%	2.26E+00	53.3%	2.10E-01	5.0%
	Eutrophication	kg PO4-eq	1.56E+00	4.18E-01	26.8%	3.44E-03	0.2%	8.57E-02	5.5%	2.30E-01	14.8%	8.22E-01	52.7%
	GWP	kg CO2 eq	1.09E+03	3.75E+02	34.5%	2.45E+00	0.2%	4.61E+01	4.2%	4.96E+02	45.7%	1.67E+02	15.4%
	ODP	kg CFC-11 eq	2.48E-05	2.05E-05	82.7%	1.33E-07	0.5%	2.72E-06	11.0%	2.70E-08	0.1%	1.40E-06	5.6%
	HT	kg 1,4-DB eq	3.30E+02	1.72E+02	52.2%	1.13E+00	0.3%	5.10E+01	15.4%	4.85E+01	14.7%	5.73E+01	17.4%



	kg SO2 eq Acidification	kg PO4-eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
END-OF-LIFE EEH	2.10E-01	8.22E-01	1.67E+02	1.40E-06	5.73E+01
END-OF-LIFE PD	4.62E-01	1.92E+00	3.89E+02	4.05E-06	1.39E+02
END-OF-LIFE GQ	4.85E-01	2.66E+00	5.14E+02	4.52E-06	1.90E+02
OPERATION EEH	2.26E+00	2.30E-01	4.96E+02	2.70E-08	4.85E+01
OPERATION PD	1.10E+01	1.12E+00	2.41E+03	1.31E-07	2.36E+02
OPERATION GQ	8.49E+00	8.65E-01	1.87E+03	1.01E-07	1.82E+02
MAINTENANCE EEH	2.41E-01	8.57E-02	4.61E+01	2.72E-06	5.10E+01
MAINTENANCE PD	4.09E-01	1.49E-01	9.19E+01	9.42E-06	1.06E+02
MAINTENANCE GQ	4.30E-01	1.42E-01	8.04E+01	8.52E-06	5.23E+01
CONSTRUCTION EEH	1.16E-02	3.44E-03	2.45E+00	1.33E-07	1.13E+00
CONSTRUCTION PD	1.74E-02	5.04E-03	3.29E+00	2.03E-07	1.56E+00
CONSTRUCTION GQ	2.51E-02	7.29E-03	4.70E+00	2.92E-07	2.32E+00
PRE-USE EEH	1.51E+00	4.18E-01	3.75E+02	2.05E-05	1.72E+02
PRE-USE PD	3.23E+00	6.19E-01	8.25E+02	2.39E-05	2.94E+02
PRE-USE GQ	2.73E+00	5.96E-01	7.30E+02	2.36E-05	2.06E+02

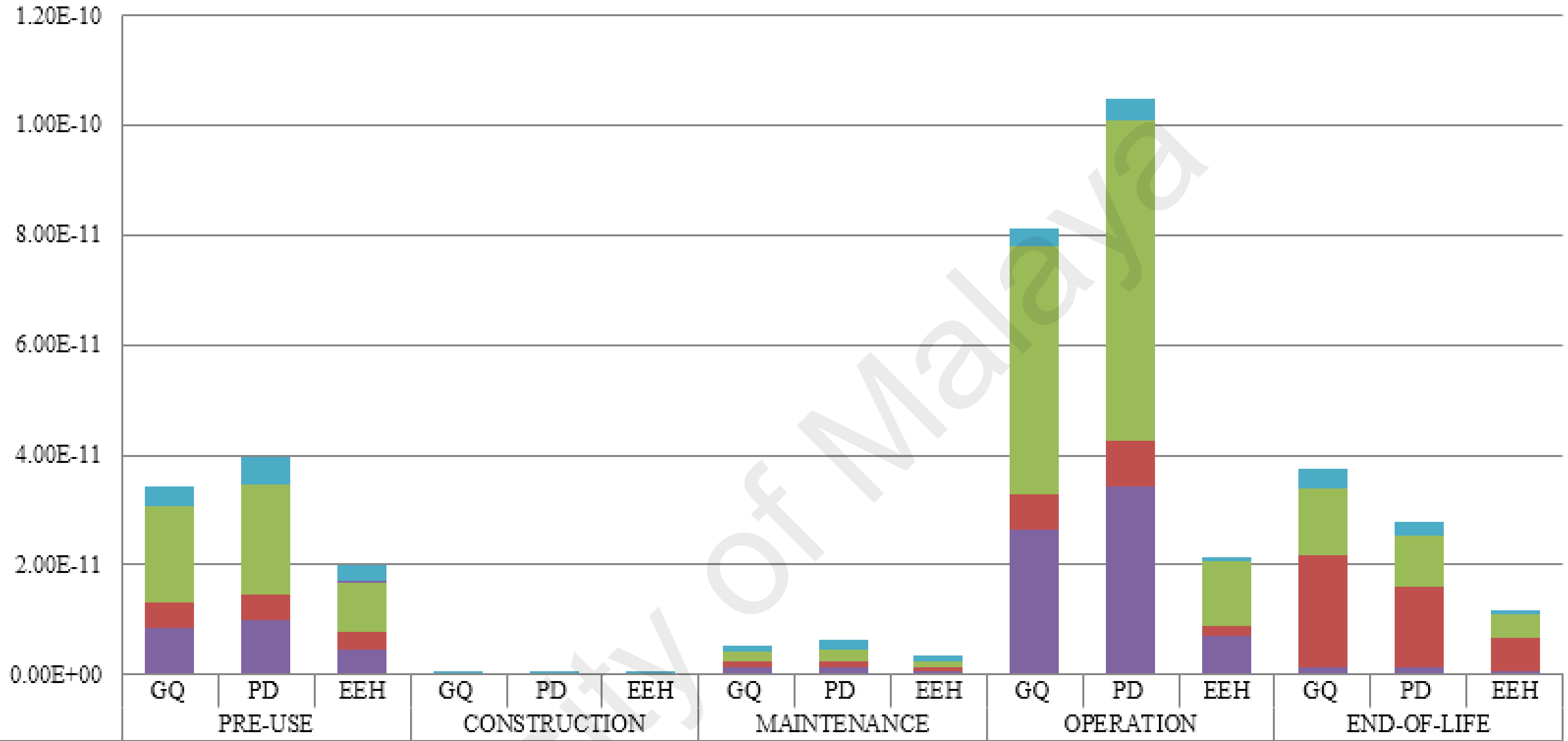
Figure 4.18: LCIA of GQ, PD and EEH from cradle-to-grave using CML 2001

Table 4.12: Quantities for EOL of building elements for GQ, PD and EEH

Building / EOL Element	Base Plaster/m3	Cement Screed/m3	Ceramic Tiles/m2	Clay Roof Tiles/m2	Concrete Blinding/m3	Concrete G25/m3	Concrete G30/m3	Concrete G35/m3	Concrete Hollow Block Wall/m2	Concrete Roof Tiles/m2
GQ	1.34E-01	3.20E-02	1.39E+00	-	3.90E-02	-	6.12E-01	8.50E-02	1.50E-02	2.50E+00
PD	7.50E-02	3.90E-02	1.45E+00	1.74E+00	8.80E-02	1.03E+00	-	-	-	-
EEH	1.80E-02	1.70E-02	4.31E-01	-	3.50E-02	-	1.66E-01	-	-	-

Building / EOL Element	Door Double Glaze/m2	Door Single Glaze/m2	Door Sliding Aluminium Frame Single Glaze/m2	Door Timber/m2	Formwork-4x usage/m2	Formwork-6x usage/ m2	Half-brick ACC block/m2	Half-brick clay/m2	One-brick ACC block/m2	One-brick clay/m2
GQ	-	-	-	5.10E-02	5.60E-01	6.30E-01	-	2.17E+00	-	1.67E-01
PD	-	2.00E-02	7.20E-02	9.70E-02	2.30E-01	6.80E-01	-	1.55E+00	-	1.51E-01
EEH	3.80E-02	-	-	-	1.10E-01	-	5.01E-01	-	8.18E-01	-

Building / EOL Element	Painting Alkyd Enamel/m2	Painting/m2	PU Insulation/m2	Rockwool Insulation/m2	Timber Product/m3	Timber Strip/m2	Window Aluminium Frame Single Glaze/m2	Window PVC Frame Double Glaze/m2	Solar Panel/m2
GQ	5.28E-01	3.75E+01	-	-	3.00E-06	2.46E-01	9.00E-02	-	-
PD	4.39E-01	2.50E+01	-	-	4.43E-02	4.72E-01	3.98E-01	-	-
EEH	-	6.35E+00	5.69E-01	1.76E+00	-	5.69E-01	-	2.30E-01	1.72E-01



	PRE-USE			CONSTRUCTION			MAINTENANCE			OPERATION			END-OF-LIFE		
	GQ	PD	EEH	GQ	PD	EEH	GQ	PD	EEH	GQ	PD	EEH	GQ	PD	EEH
Human toxicity	3.60E-12	5.14E-12	3.01E-12	4.06E-14	2.73E-14	1.98E-14	9.15E-13	1.86E-12	8.92E-13	3.19E-12	4.13E-12	8.49E-13	3.32E-12	2.43E-12	1.00E-12
Ozone layer depletion (ODP)	4.58E-14	4.63E-14	3.98E-14	5.67E-16	3.94E-16	2.58E-16	1.65E-14	1.83E-14	5.27E-15	1.97E-16	2.55E-16	5.23E-17	8.77E-15	7.85E-15	2.71E-15
Global warming (GWP100)	1.76E-11	1.99E-11	9.04E-12	1.13E-13	7.93E-14	5.90E-14	1.94E-12	2.22E-12	1.11E-12	4.50E-11	5.82E-11	1.20E-11	1.24E-11	9.37E-12	4.02E-12
Eutrophication	4.50E-12	4.68E-12	3.16E-12	5.51E-14	3.81E-14	2.60E-14	1.07E-12	1.13E-12	6.48E-13	6.54E-12	8.46E-12	1.74E-12	2.01E-11	1.45E-11	6.21E-12
Acidification	8.50E-12	1.00E-11	4.71E-12	7.81E-14	5.40E-14	3.60E-14	1.34E-12	1.27E-12	7.49E-13	2.64E-11	3.42E-11	7.02E-12	1.51E-12	1.44E-12	6.52E-13

Figure 4.19: Normalisation of LCIA of GQ, PD and EEH from cradle-to-grave using CML 2001

4.6.3 *Endpoint environmental damage using Eco-indicator 99*

4.6.3.1 Introduction

Eco-indicator 99 was used to measure the environmental impact of GQ, PD, and EEH from cradle-to-grave in endpoint as suggested by previous research. The method used are hierarchist version with average (H/A) weighting setting as recommended by PRé Consultants in SimaPro. The impact was calculated as single score with ecopoints in three (3) different damage categories namely Human Health (HH), Ecosystem Quality (EQ) and Resources (R).

HH will refer to the damages affecting human health measured for carcinogens, climate change, ionising radiation, ozone layer depletion, respiratory organics, and respiratory inorganics. EQ will refer to the damages to climate change, radiation, ozone layer, ecotoxicity and acidification/eutrophication. R will refer to the damages affecting resources depletion i.e. land use, minerals and fossil fuels. Based on the expert discussion of Swiss LCA interest group indicates that damages to HH and EQ is equally important, but R is about half as important as the other (Pré Consultant, 2000).

	Pt Human Health	Pt Ecosystem Quality	Pt Resources
END-OF-LIFE EEH	1.57E+01	4.82E+00	7.12E+01
END-OF-LIFE PD	3.59E+01	1.14E+01	1.43E+02
END-OF-LIFE GQ	4.88E+01	1.59E+01	1.56E+02
OPERATION EEH	2.55E+01	9.21E-01	8.30E+02
OPERATION PD	1.24E+02	4.48E+00	4.04E+03
OPERATION GQ	9.57E+01	3.46E+00	3.12E+03
MAINTENANCE EEH	2.98E+00	5.76E-01	6.91E+00
MAINTENANCE PD	4.59E+00	1.16E+00	1.10E+01
MAINTENANCE GQ	4.27E+00	1.18E+00	1.02E+01
CONSTRUCTION EEH	1.53E-01	1.72E-01	1.07E+00
CONSTRUCTION PD	2.34E-01	7.65E-01	1.81E+00
CONSTRUCTION GQ	3.42E-01	1.10E+00	2.86E+00
PRE-USE EEH	2.08E+01	2.15E+00	1.31E+02
PRE-USE PD	4.16E+01	5.87E+00	3.25E+02
PRE-USE GQ	3.80E+01	2.80E+00	2.82E+02

Figure 4.20: Weighting of LCIA of GQ, PD, and EEH from cradle-to-grave using Eco-indicator 99H/A

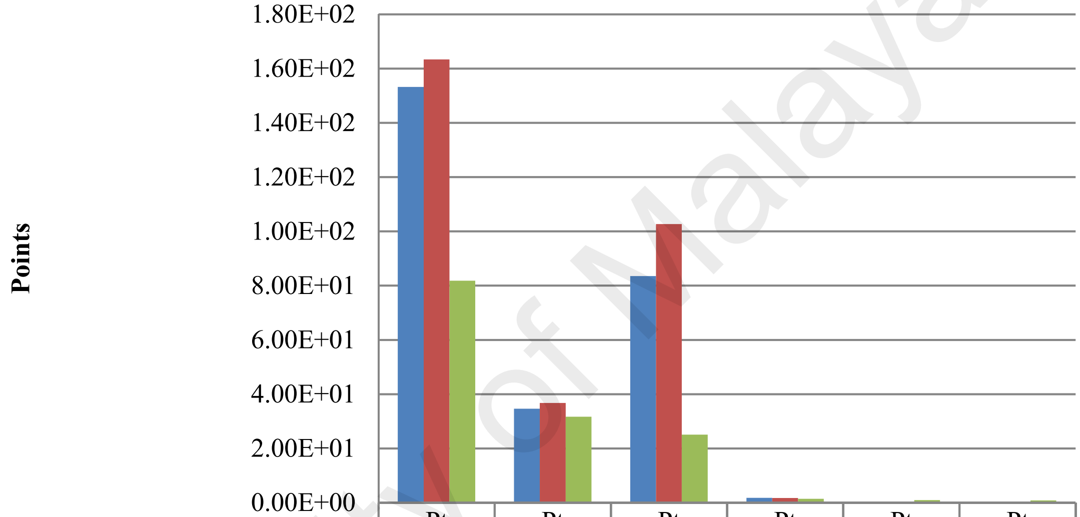
4.6.3.2 General Results

Figure 4.20 shows the weighting of environmental impact distribution of all case studies using Eco-indicator 99H/A. The findings from Eco-indicator 99 and CML 2001 shows a similar pattern where PD has the largest impact overall. The impact on resource depletion scored the highest point on all stage of construction especially in operation stage which will be discussed further in this chapter. The pre-use and EOL phases in second and third position, but if compared with the operation results, it is considerably lower specifically in resource depletion. Table 4.13 shows the weighting points for all case studies during the pre-use phase. In resource depletion damage category, the fossil fuel depletion shows the highest point on GQ (2.81E+02 point), PD (3.13E+02) and EEH (1.48E+02). The usage of diesel for transportation shows the highest followed by cement usage and also electricity usage during production. The data for transportation will be assessed later on by using sensitivity analysis later in this chapter to compare the impact of distances to emissions.

Table 4.13: Weighting of LCIA of GQ, PD and EEH during pre-use phase using Eco-Indicator 99H/A

Impact category	Unit	GQ Pre-use 5% Wastage	PD Pre-use with 5% wastage	EEH Pre-use with 5% wastage
Total	Pt	3.23E+02	3.60E+02	1.73E+02
Carcinogens	Pt	3.72E+00	3.76E+00	3.15E+00
Resp. organics	Pt	1.80E-02	1.86E-02	1.66E-02
Resp. inorganics	Pt	2.72E+01	2.92E+01	1.45E+01
Climate change	Pt	6.99E+00	7.64E+00	3.74E+00
Radiation	Pt	4.79E-02	4.60E-02	3.98E-02
Ozone layer	Pt	1.13E-03	1.14E-03	1.11E-03
Ecotoxicity	Pt	1.05E+00	1.17E+00	1.01E+00

Impact category	Unit	GQ Pre-use 5% Wastage	PD Pre-use with 5% wastage	EEH Pre-use with 5% wastage
Acidification/ Eutrophication	Pt	9.85E-01	1.09E+00	5.69E-01
Land use	Pt	7.81E-01	3.55E+00	7.16E-01
Minerals	Pt	6.70E-01	4.57E-01	6.46E-01
Fossil fuels	Pt	2.81E+02	3.13E+02	1.48E+02



	Pt Diesel	Pt Electricity	Pt Cement	Pt Natural Gas	Pt PVC	Pt Petrol
GQ Preuse 5% Wastage	1.53E+02	3.46E+01	8.35E+01	1.73E+00	1.74E-03	0.00E+00
PD Pre-use with 5% wastage	1.63E+02	3.67E+01	1.03E+02	1.72E+00	1.83E-03	0.00E+00
EEH Pre-use with 5% wastage	8.18E+01	3.17E+01	2.50E+01	1.41E+00	9.52E-01	8.22E-01

Figure 4.21: Process contribution of fossil fuels depletion during pre-use using Eco-indicator 99 H/A with 0.5% cut-off

4.7 Discussion on energy consumptions and materials selections

4.7.1 *Comparison results in energy consumption*

4.7.1.1 Introduction

Similar to previous findings from other researcher, energy consumptions were identified as the largest impact on the environment. The electricity mix generation in Malaysia is different with other countries as the main source of production are fossil fuel. The power stations in Malaysia are consist of gas-fired, coal-fired, gas and coal-fired, oil-fired and hydro, but natural gas is the highest main fuel source (MY-LCID, 2013). Electricity generated by fossil fuels contribute to high GHG, which contributed to global warming.

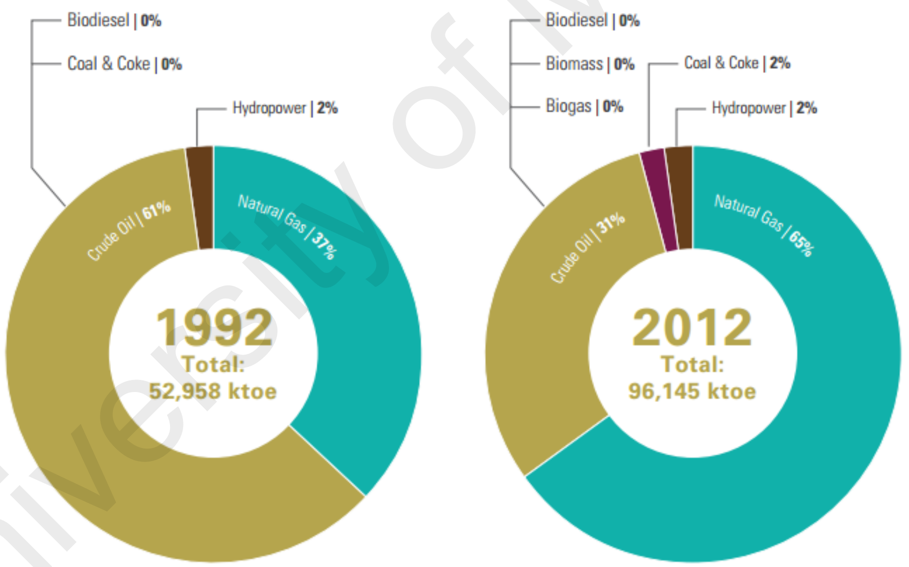
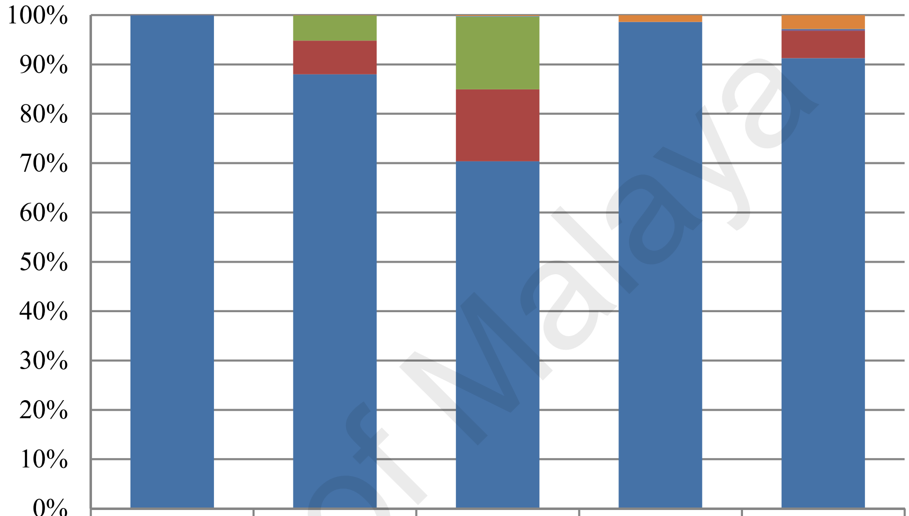


Figure 4.22: Electricity mix generation in Malaysia for the year 1992 and 2012 (Suruhanjaya_Tenaga, 2014)

The environmental impact of electricity generation in Malaysia is high in comparison with European countries as shown in Figure 4.24. The effort of harnessing renewable resources such as hydropower, wind, biomass, geothermal and solar for electricity generation in Malaysia need to improve to lower the environmental impact as has been done in European countries. In comparison to other neighbouring countries within the South East Asia (Asean) such as Brunei, Indonesia, Philippines, Singapore, and Thailand the electricity mix generation is quite similar to fossil fuel as the main source of energy (EIA, 2015).



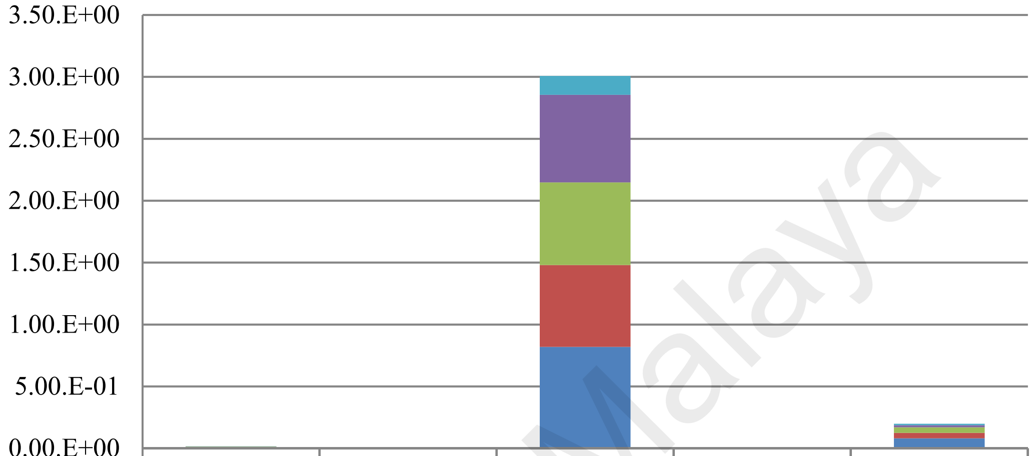
	Brunei	Indonesia	Philippines	Singapore	Thailand
Biomass and Waste	0.00%	0.09%	0.24%	1.40%	2.81%
Wind	0.00%	0.00%	0.11%	0.00%	0.09%
Solar	0.05%	0.00%	0.00%	0.03%	0.32%
Geothermal	0.00%	5.08%	14.71%	0.00%	0.00%
Hydroelectric	0.00%	6.84%	14.57%	0.00%	5.54%
Total Fossil Fuels	99.95%	87.99%	70.38%	98.57%	91.25%

Figure 4.23: Electricity Generation Mix for Selected Asean Countries in 2012 (EIA, 2015)

4.7.1.2 Midpoint environmental impact distribution of electricity generation in comparison to other countries

Figure 4.24 shows the midpoint environmental impact of electricity generation of 1 kWh in Malaysia, Great Britain, Spain, Germany, and France by using CML 2001. Malaysia has the highest impact on eutrophication, GWP and HT, the third highest in acidification and the lowest in ODP.

In acidification, four (4) substances were measured which is sulfur dioxide, nitrogen oxides, ammonia and nitric oxide. The acidification emission is measured in kg SO_2 eq. Malaysia acidification impact is third overall, but it has the largest emission of nitrogen oxides compare to other countries.



	kg SO2 eq Acidification	kg PO4 eq Eutrophicatio n	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
France	5.42.E-04	4.15.E-05	1.53.E-01	3.11.E-07	1.13.E-02
Germany	1.21.E-03	9.40.E-05	7.07.E-01	1.17.E-07	1.64.E-02
Spain	5.17.E-03	2.06.E-04	6.69.E-01	1.12.E-07	4.51.E-02
Great Britain	3.94.E-03	1.77.E-04	6.61.E-01	9.76.E-08	4.44.E-02
Malaysia	3.73.E-03	3.80.E-04	8.19.E-01	4.45.E-11	8.00.E-02

Figure 4.24: Comparison of LCIA of electricity mix generation for 1kWh in Malaysia, Great Britain, Spain, Germany, and France by using CML 2001

The eutrophication level is significantly higher in Malaysia (3.80E-04 kg PO_4 eq) due to the high emission of nitrogen oxides, chemical oxygen demand (COD), phosphate and ammonia. In GWP, the impact in Malaysia is marginally higher (8.19E+01 kg CO_2 eq) due to the release of carbon dioxide from fossil fuels as shown in Figure 4.22. In HT, the emission of arsenic (5.12E-02 kg 1,4 DB eq) to air is significantly higher in Malaysia thus reflected the overall result.

4.7.1.3 Energy consumption for buildings

The final energy consumptions for the 3 case studies were analysed in Table 4.2, Table 4.6 and Table 4.9. Air conditioning has been identified as the largest consumer of electrics. The air conditioning system in EEH consumes 57% from the total energy due to the 24-hour operations for the whole area. The GQ and PD air conditioning system were estimated below than 50% (41.5% and 45.3% respectively) but with only 8 hours of operation (10 pm to 6 am). The slightly larger rooms in PD results in higher overall energy consumptions with a larger area to illuminate and cool. In EEH, the installation of proper insulation to wall, floor, and roof including the double glazing windows helped to reduce the overall thermal transfer value (OTTV) of the house resulting less energy use to cool down the house.

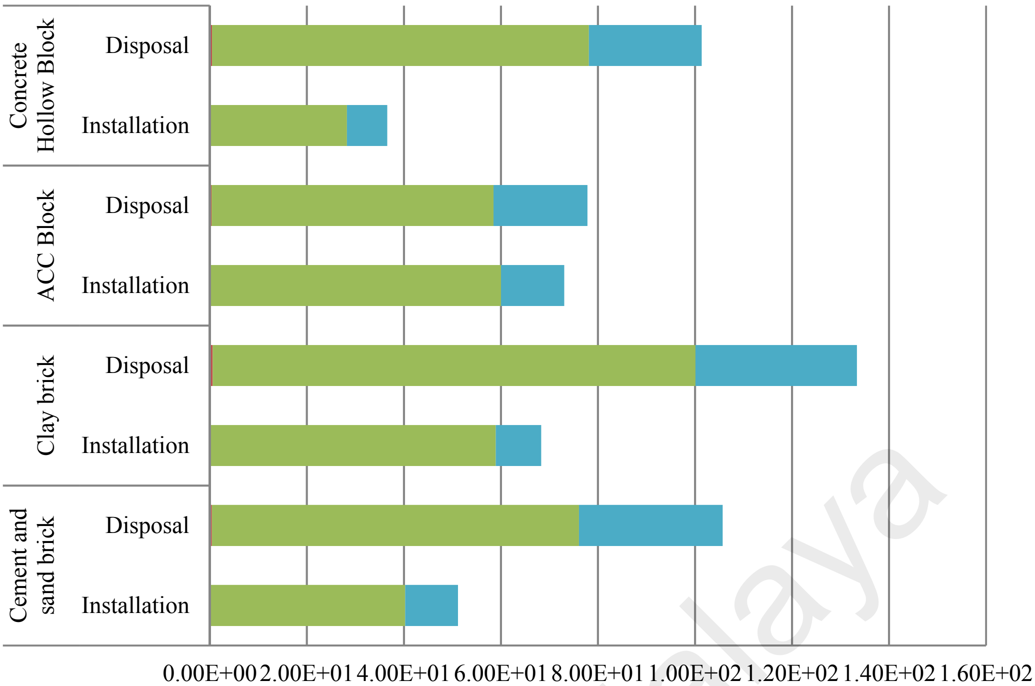
4.7.2 *Comparison Results for Materials and Construction Selection*

The materials and the construction methods used in these three buildings are different particularly in EEH. The materials in EEH are specifically selected to provide comfortable environment by reducing the overall energy consumption by preventing heat transfer from outside and also cold air seepage (Boswell & Bacon, 2009). The materials selection for GQ are within the standard specification for all government buildings, but PD is subject to the architect and engineers design and developer’s budget within the Malaysian standards requirement. In this section, various choices of materials and construction methods were evaluated and discussed.

4.7.2.1 Types of Bricks

Bricks are the main building materials used in the building envelope and partitions of for all case studies. Both GQ and PD used clay bricks as the main material while autoclaved aerated concrete (AAC) block was used in EEH. Another type of brick that commonly use in Malaysia is cement and sand bricks and concrete blocks. These bricks usually being used for low to middle-cost houses due to its lower price per brick. The manufacturing process and the raw materials of these bricks are different thus resulting in different impact results. Four (4) type of bricks namely clay bricks, AAC bricks, cement and sand brick and concrete blocks of $1m^2$ of wall area from cradle-to-grave were being assessed using CML 2001.

Figure 4.25 shows the characterization of each brick and disposal. Clay bricks disposal contribute the highest impact on eutrophication, GWP, and HT, and the manufacturing of clay bricks contribute to the highest ODP. ACC block has been identified as a contributor to the highest acidification impact. Cement has been identified as the highest impact contributor for acidification, eutrophication, GWP and HT in cement-based brick i.e. cement and sand brick, AAC brick and concrete block. Considering all process from cradle-to-grave, clay bricks has the highest impact overall; concrete block has the lowest in GWP, ODP, and HT; cement and sand bricks has the lowest acidification impact, and ACC block has the lowest eutrophication impact.



	Cement and sand brick		Clay brick		ACC Block		Concrete Hollow Block	
	Installation	Disposal	Installation	Disposal	Installation	Disposal	Installation	Disposal
Acidification kg SO2 eq	1.67E-01	3.01E-02	1.79E-01	1.12E-01	2.07E-01	6.67E-02	1.26E-01	1.25E-01
Eutrophication kg PO4 eq	3.15E-02	4.16E-01	3.99E-02	4.83E-01	3.67E-02	2.81E-01	2.40E-02	3.44E-01
GWP kg CO2 eq	4.01E+01	7.56E+01	5.87E+01	9.95E+01	5.98E+01	5.81E+01	2.81E+01	7.77E+01
ODP kg CFC-11 eq	1.35E-06	6.41E-07	3.23E-06	6.54E-07	2.34E-06	3.81E-07	5.78E-07	4.70E-07
HT kg 1,4-DB eq	1.09E+01	2.96E+01	9.35E+00	3.33E+01	1.30E+01	1.94E+01	8.32E+00	2.32E+01

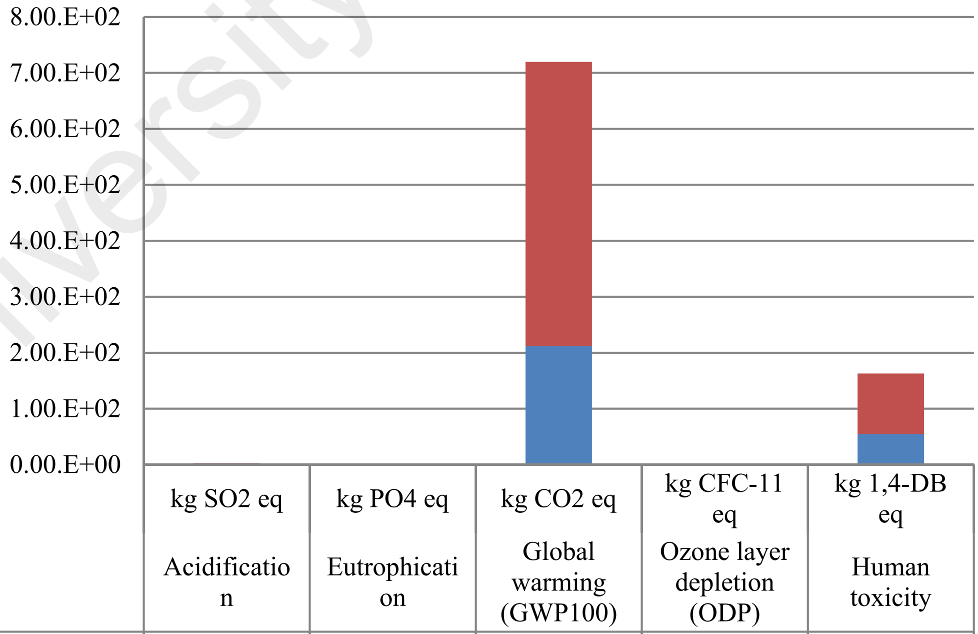
Figure 4.25: Comparison of characterization of LCIA of 1m^2 of wall including disposal of cement and sand brick, clay brick, AAC block and concrete block by using CML 2001

4.7.2.2 Reinforced Concrete Structure and Load Bearing Walls

The conventional residential and commercial buildings in Malaysia use reinforced concrete structure that consists of columns and beams with bricks enclosure. The load bearing wall system is rarely being used in conventional residential buildings in Malaysia although currently it is being encouraged through the IBS initiative (Ramli, Abdullah, Nasrun, & Nawi, 2014). EEH uses AAC concrete block load bearing wall system while others are reinforced concrete structure with clay bricks.

As shown in Figure 4.25, ACC block has the lower impact for total life cycle, however, this result does not represent the construction system as it does not include the building frames i.e. columns and beams. To compare the overall wall system, 1 m^2 of GFA of each building were assessed which include wall and frames. The assessment also included the substructure as these two buildings have different construction method i.e. pad foundation for PD and strip foundation for EEH, which has an influence on the quantity of material used.

Figure 4.26 shows the comparison of two different structures. The reinforced concrete frame structure has approximately doubled the LCIA as compared to the load bearing wall structure that contributed largely by cement. PD uses more cement in the production of reinforced concrete which contributed to the larger impact overall. Cement contributed to the highest LCIA as shown in Table 4.14 excluding in ODP, which was dominated by the production of crude oil.



	kg SO2 eq Acidification	kg PO4 eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
1m2 GFA of PD	2.01.E+00	3.36.E-01	5.08.E+02	1.05.E-05	1.08.E+02
1m2 GFA of EEH	8.07.E-01	1.57.E-01	2.12.E+02	6.46.E-06	5.50.E+01

Figure 4.26: Comparison of LCIA of load bearing wall for 1 m2 GFA for EEH and RC frame and clay brick in PD by using CML 2001

Table 4.14: Percentage of cement in overall LCIA of 1 m^3 of concrete grade 30

Impact category	**Unit**	**% of LCIA of Cement**
Acidification	kg SO_2 eq	93.60%
Eutrophication	kg PO_4 eq	83.50%
Global warming (GWP100)	kg CO_2 eq	95.50%
Ozone layer depletion (ODP)	kg CFC-11 eq	2.38%
Human toxicity	kg 1,4-DB eq	81.20%

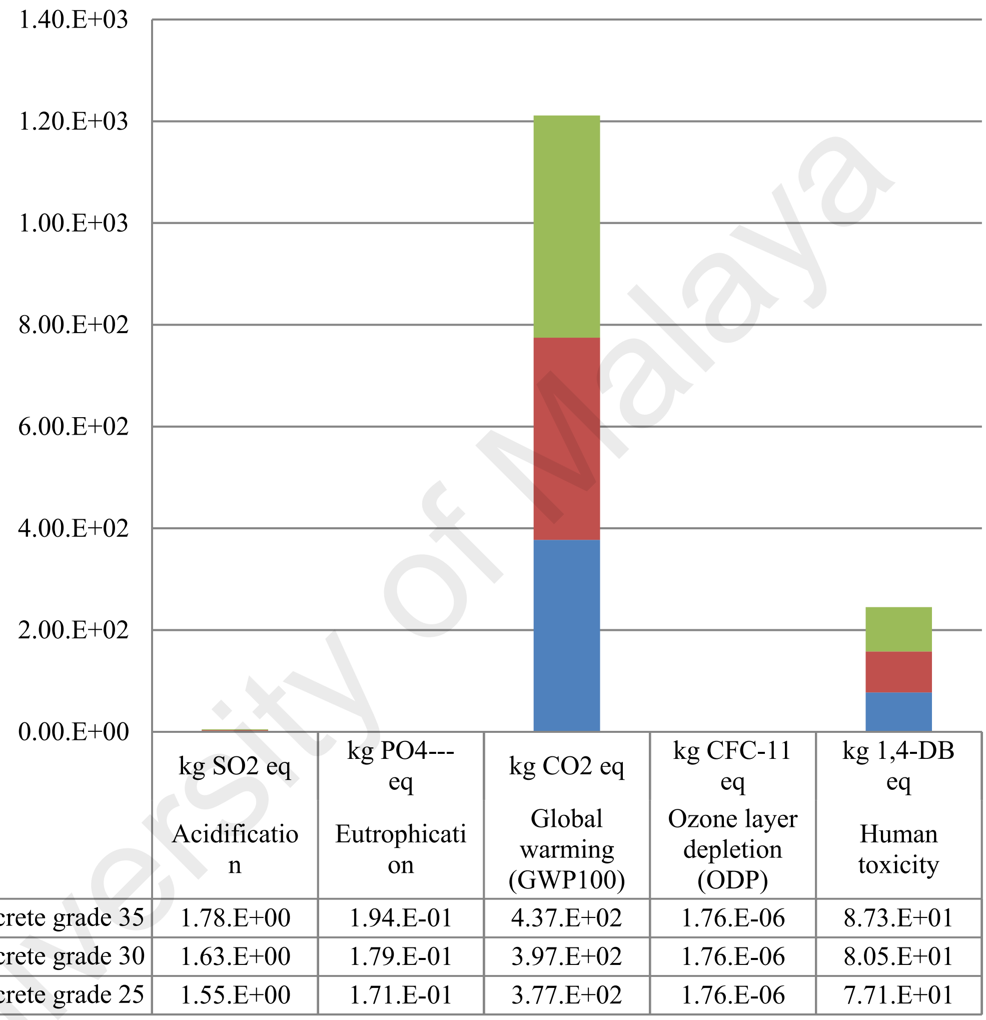
4.7.2.3 Concrete Grades

There are three grades used in the buildings namely grade 25, 30 and 35. Each grade represents different strength of concrete by combining different design mix of basic materials which is cement, sand, gravel and water. The mixtures of concrete may be different between manufacturers. For this research, the design mix was selected from a concrete manufacturer in Malaysia (Prototech, 2014) to reflect local design mix as tabulated in Table 4.15.

Table 4.15: Concrete design mix for 1m^3 in different grades of concrete

Concrete Grade	**Cement (kg)**	**Sand (kg)**	**Gravel (kg)**	**Water (kg)**
25	360	860	970	180
30	380	840	980	180
35	420	800	980	180

The concrete grades represent the characteristic strength of the concrete at 28 days in N/mm^2. The lower the grades, the lower the strength of concrete. Grade 25 are used in PD, while grade 30 is used in EEH and GQ uses grade 30 and 35. The price of concrete per m^3 is subject to the grades. Higher the grade of concrete means more expensive. The environmental impact of different grades of concrete is shown as in Figure 4.27. The results show that the higher the grades, the higher impact due to the increased quantity of cement. Cement is identified as the highest contributor to the environmental impact of 1 m^3 of concrete as shown in Table 4.14. The impact of cement production in Malaysia was also identified to have higher LCIA in comparison to cement production in Switzerland as shown in Table 4.16.



	kg SO2 eq Acidification	kg PO4--- eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
Concrete grade 35	1.78.E+00	1.94.E-01	4.37.E+02	1.76.E-06	8.73.E+01
Concrete grade 30	1.63.E+00	1.79.E-01	3.97.E+02	1.76.E-06	8.05.E+01
Concrete grade 25	1.55.E+00	1.71.E-01	3.77.E+02	1.76.E-06	7.71.E+01

Figure 4.27: LCIA of 1m^3 of concrete grade 25, 30 and 35 by using CML 2001

Table 4.16: LCIA of 1 kg of cement in Malaysia (MY) and Switzerland (CH) by using CML 2001

Impact category	**Unit**	**Cement (MY)**	**Cement (CH)**
Acidification	kg SO_2 eq	4.00.E-03	1.09.E-03
Eutrophication	kg PO_4 eq	3.93.E-04	2.47.E-04
Global warming (GWP100)	kg CO_2 eq	9.99.E-01	7.60.E-01
Ozone layer depletion (ODP)	kg CFC11 eq	1.10.E-10	2.16.E-08
Human toxicity	kg 1,4-DB eq	1.72.E-01	6.07.E-02

4.7.2.4 Recycling Potential

The potential of recycling was recently highlighted due to the ability to reduce the overall environmental impact. A recent study by Arham (2008) has identified that only steel and aluminium are being regularly recycled in Malaysia, and other materials are transported to the landfill. In SimaPro, the recycling process is cut-off and to evaluate the benefit of recycling, the use of primary materials should be considered as avoided product and scrap materials used as input from technosphere. Therefore, the used of pig iron and primary aluminium will be considered as avoided product and replaced with scrap iron and old aluminium scrap respectively as suggested in SimaPro.

As mentioned earlier, two materials were considered to be recycled which are steel and aluminium. To measure the recycling potential of these two items, a comparison analysis of two data processes were conducted between a recycle and a non-recycle namely 1 kg of steel reinforcement and 1 m^2 of the aluminium window frame. The reduction of environmental impact is very significant in both building materials as shown in Table 4.17.

Table 4.17: Estimated reduction of environmental impact by recycling of steel and aluminium using CML 2001

Impact category	Unit	Steel Reinforcement (1 kg)				Aluminium Window Frame (1 m2)			
		Recycle	Normal	Reduction		Recycle	Normal	Reduction	
Acidification	kg SO_2 eq	2.12.E-03	6.76.E-03	4.64.E-03	(69%)	6.22.E-01	2.09.E+00	1.47.E+00	(70%)
Eutrophication	kg PO_4 eq	1.64.E-03	3.99.E-03	2.36.E-03	(59%)	3.02.E-01	7.88.E-01	4.87.E-01	(62%)
Global warming (GWP100)	kg CO_2 eq	6.22.E-01	1.75.E+00	1.13.E+00	(64%)	1.63.E+02	4.77.E+02	3.15.E+02	(66%)
Ozone layer depletion (ODP)	kg CFC-11 eq	4.31.E-08	6.88.E-08	2.57.E-08	(37%)	1.47.E-05	3.34.E-05	1.87.E-05	(56%)
Human toxicity	kg 1,4-DB eq	5.29.E-01	7.20.E+00	6.67.E+00	(93%)	4.23.E+02	1.92.E+03	1.50.E+03	(78%)

4.8 Data Validation

4.8.1 *Introduction*

4.8.2 *Comparison with Other Findings*

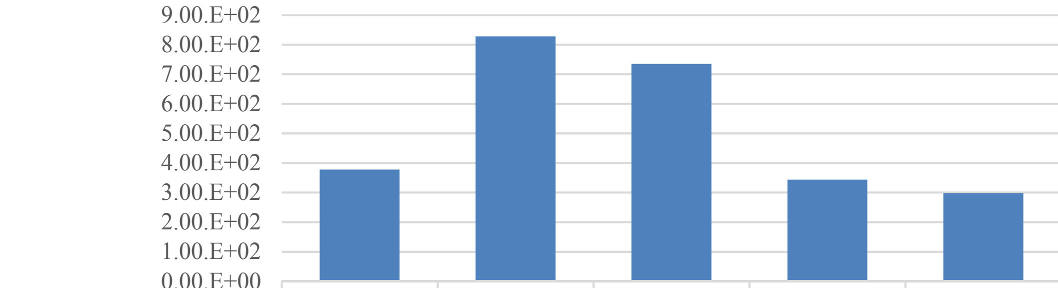
At this moment, there are no full LCA studies for Malaysian residential building; therefore, the comparison is not possible. As an alternative, this research will compare the results from cradle-to-gate with 4-storey conventional and IBS flats (Wen et al., 2014). Further comparison will consist of a cradle-to-grave of a terrace, semi-detached and detached houses in the UK (Cuéllar-Franca & Azapagic, 2012) and also a semi-detached house in Spain (Ortiz-Rodríguez et al., 2010) with selected impact categories.

Figure 4.28 shows the comparison of a 4-storey conventional and IBS flat in Malaysia and the case studies while Figure 4.29 shows the comparison with a semi-detached house in Spain, a terrace, semi-detached and detached houses in the UK. The comparison with the flat is only limited to GWP as it is the only similar impact category. The GWP of the case studies was much higher than the flat. The comparison for these buildings may not be accurate as these are different type of buildings. The material specification and the quantity per m^2 also contributed to the differences in the impact. For example, detail specification of the brick and concrete used in the flats was not clearly mentioned. The energy used to produce cement-based brick is much lower than clay bricks that have an impact in the overall GWP (Utama & Gheewala, 2008). The different concrete grades also will have a different overall impact due to the different mix ratio of cement, sand, and gravel. The shared elements between multiple units inside the flat such as roof, wall, floor and ceiling also reduced the impact per m^2 GFA.

The comparison of GWP impact category for cradle-to-grave between the case studies to other buildings was relatively comparable. Only GWP results were available in detail for the UK houses, therefore other impact categories were omitted. Since the largest share of GWP is from the use phase, the method used in determining the energy consumptions, climates and impact from electricity generation in different countries could have produced different results. The energy consumption in Ortiz et al. (Ortiz et al., 2009) is estimated by simulation software DesignBuilder using weather condition in Barcelona while Cuéllar-Franca et al. (Cuéllar-Franca & Azapagic, 2012) calculated using statistic of domestic energy consumption in the UK and own estimates. The environmental impact of electricity generation is also different as Malaysia produces the highest GWP and HT and the lowest ODP per kWh as shown in Figure 4.24.

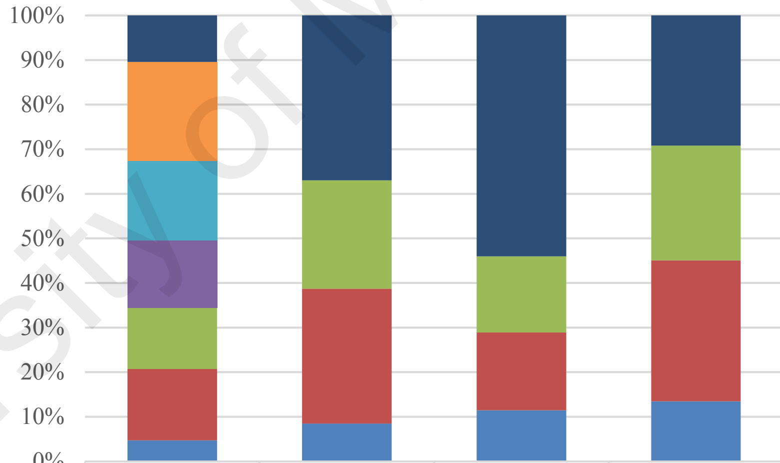
All studies indicated that the use phase of the building has the largest GWP, acidification, and HT which similar to this research. The ODP impact was primarily the highest in the pre-use phase for all buildings excluding in Spain. The use phase was identified as the largest contributor to ODP in Spain due to a higher level of ODP in the electricity generation in comparison to Malaysia and UK as shown in Figure 4.24. Overall results show that EEH has the lowest cradle-to-grave LCIA as compared to other buildings mainly due to the lower energy consumption during the use phase.

Another factor that may reflect the LCIA result is the LCA software use in these studies. A recent study by Herrmann & Moltesen (2015) suggested that there are differences in LCIA result if the assessment is conducted using different LCA software such as SimaPro and GaBi. The study also suggested that the LCIA results from using different software were relatively compatible if using CML 2001 is used compared to Eco-indicator 99 and EDIP 2003.



	Detached - EEH (This Study)	Semi-Detached - PD (This Study)	Semi-Detached - GQ (This Study)	Conventional Flat (Wen et al, 2015)	IBS Flat (Wen et al, 2015)
Global warming Potential (GWP100) kg CO2 eq	3.78.E+02	8.28.E+02	7.35.E+02	3.44.E+02	2.98.E+02

Figure 4.28: Comparison of selected impact categories of a 4-storey IBS and conventional flat in Malaysia (Wen et al., 2014) and the case studies.



	Global warming (GWP100)	Acidification	Ozone layer depletion (ODP)	Human toxicity (HT)
Semi-detached (Ortiz et al, 2009)	2.43.E+03	1.85.E+01	1.17.E-04	7.18.E+02
Terrace (Cuéllar-Franca, 2012)	5.15.E+03			
Semi-Detached (Cuéllar-Franca, 2012)	4.16.E+03			
Detached (Cuéllar-Franca, 2012)	3.50.E+03			
Semi-Detached - GQ (This Study)	3.19.E+03	1.22.E+01	3.70.E-05	6.32.E+02
Semi-Detached - PD (This Study)	3.72.E+03	1.51.E+01	3.77.E-05	7.77.E+02
Detached - EEH (This Study)	1.09.E+03	4.23.E+00	2.48.E-05	3.30.E+02

Figure 4.29: Comparison of selected impact categories of a semi-detached house in Spain (Ortiz et al., 2009), a detached, semi-detached and detached house in the UK (Cuéllar-Franca & Azapagic, 2012), and the case studies.

4.9 Sensitivity analysis

4.9.1 *Introduction*

The sensitivity analysis is a process that recalculates the LCA based on the changes in assumptions that have been made. The purpose of this process is to get a better understanding of the magnitude of the set assumption (Goedkoop et al., 2010).

4.9.2 *Changing transportation distances*

This step had been conducted to determine the influence of assumption in this research. The transportation distance of materials to the construction site as the distance is based on literature suggested by Wittstock et al. (Wittstock et al., 2012). The predetermined distance set is 50 km for concrete and 300 km for other materials. The standard deviation of ±20% is allocated for transportation distance as suggested by Wen, Siong, and Noor (Wen et al., 2014). For transportation analysis, only substructure in PD is used as base case scenarios as it has the largest impact overall. The results show that the transportation distances do not have a significant impact overall with a maximum effect of 8.78% in ODP while other impact categories are below 6% differences as shown in

Table **4.18**.

Table 4.18: Results of LCIA with ±20% standard deviation for transportation distance for substructure

Impact category	Unit	Percentage
Acidification	kg SO_2 eq	3.06%
Eutrophication	kg PO_4 eq	5.51%
Global warming (GWP100)	kg CO_2 eq	2.54%
Ozone layer depletion (ODP)	kg CFC-11 eq	8.78%
Human toxicity	kg 1,4-DB eq	1.85%

4.9.3 *Changing building lifespan*

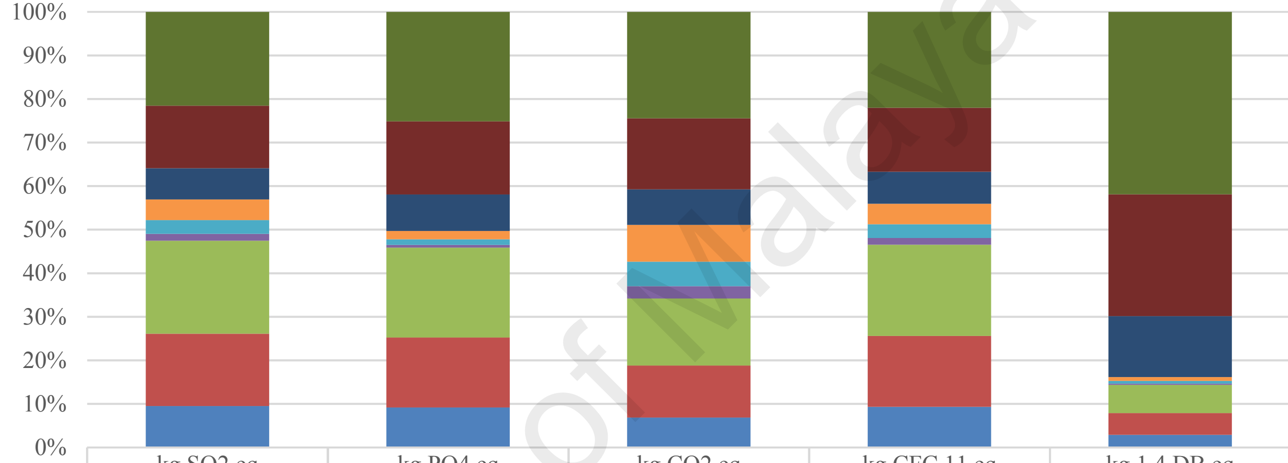
The building lifespan in this research was assumed to be 50 years which was primarily used by most LCA research. The selected lifespan reflects the final energy consumption and LCIA. However, there are a few studies that estimated the lifespan of the building span between 40 to 100 years. Therefore, the sensitivity analysis of the LCIA of different building lifespans will be assessed and compared to the findings. The new lifespans are assumed to be 75 years and 100 years. The changes in the building lifespan will alter the total energy consumption and the maintenance frequencies of selected building elements. For this purpose, only data for PD will be used as it consumed the largest energy and had the highest levels in most environmental impacts.

4.9.3.1 Impacts in maintenance phase

The replacement interval for painting, roof covering and windows was assumed to be similar with expected lifespan of 10, 25 and 30 years respectively. The number of replacement in 75 and 100 years as shown in Table 4.19. The LCIA of the PD with new lifespan is shown in Figure 4.30: Sensitivity analysis of building lifespan impact on building elements in the maintenance phase using CML 2001.Figure 4.30.

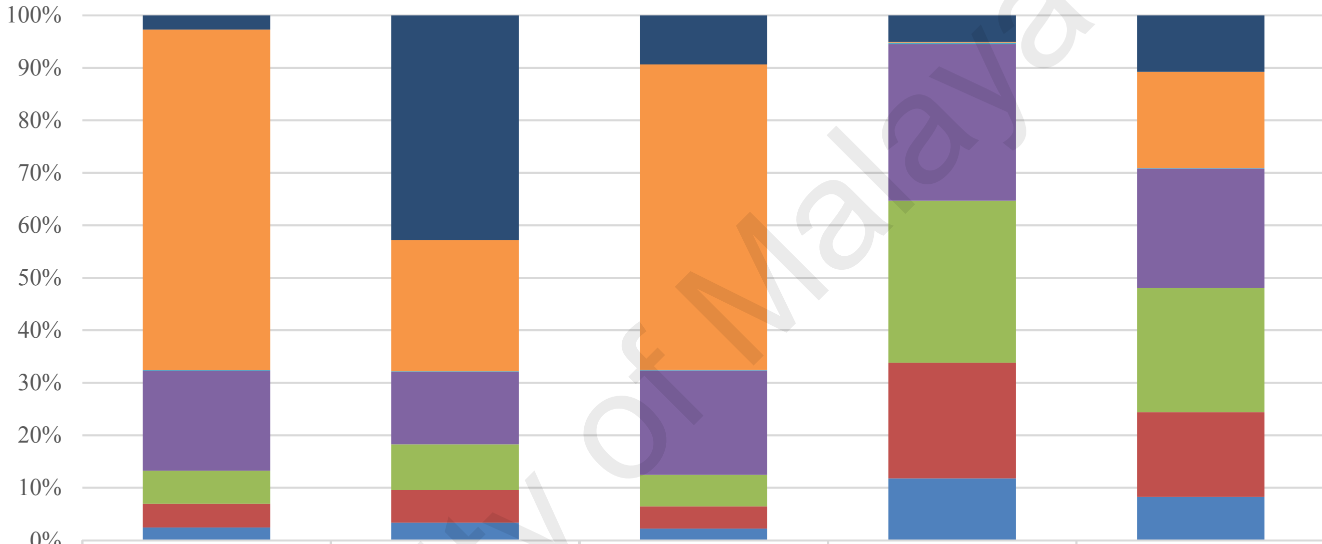
Table 4.19: Sensitivity analysis of replacement interval of selected building elements in maintenance phase

Elements	**Expected Lifespan**	**Number of replacement in 75 years**	**Number of replacement in 100 years**
Painting	10 years	7 times	9 times
Roof covering	25 years	2 times	3 times
Window	30 years	2 times	3 times



	kg SO_2 eq Acidification	kg PO_4 eq Eutrophication	kg CO_2 eq Global warming (GWP100)	kg CFC 11 eq Ozone layer depletion (ODP)	kg 1,4 DB eq Human toxicity
Aluminium Window - 100 years	4.83.E-01	2.06.E-01	1.26.E+02	1.14.E-05	2.60.E+02
Aluminium Window - 75 years	3.22.E-01	1.38.E-01	8.42.E+01	7.59.E-06	1.73.E+02
Aluminium Window - 50 years	1.61.E-01	6.88.E-02	4.21.E+01	3.79.E-06	8.66.E+01
Clay Roof Tiles - 100 years	1.06.E-01	1.56.E-02	4.37.E+01	2.44.E-06	5.61.E+00
Clay Roof Tiles - 75 years	7.08.E-02	1.04.E-02	2.91.E+01	1.63.E-06	3.74.E+00
Clay Roof Tiles - 50 years	3.54.E-02	5.20.E-03	1.46.E+01	8.13.E-07	1.87.E+00
Painting - 100 years	4.79.E-01	1.69.E-01	7.94.E+01	1.08.E-05	4.00.E+01
Painting - 75 years	3.72.E-01	1.32.E-01	6.18.E+01	8.41.E-06	3.11.E+01
Painting - 50 years	2.13.E-01	7.52.E-02	3.53.E+01	4.81.E-06	1.78.E+01

Figure 4.30: Sensitivity analysis of building lifespan impact on building elements in the maintenance phase using CML 2001.



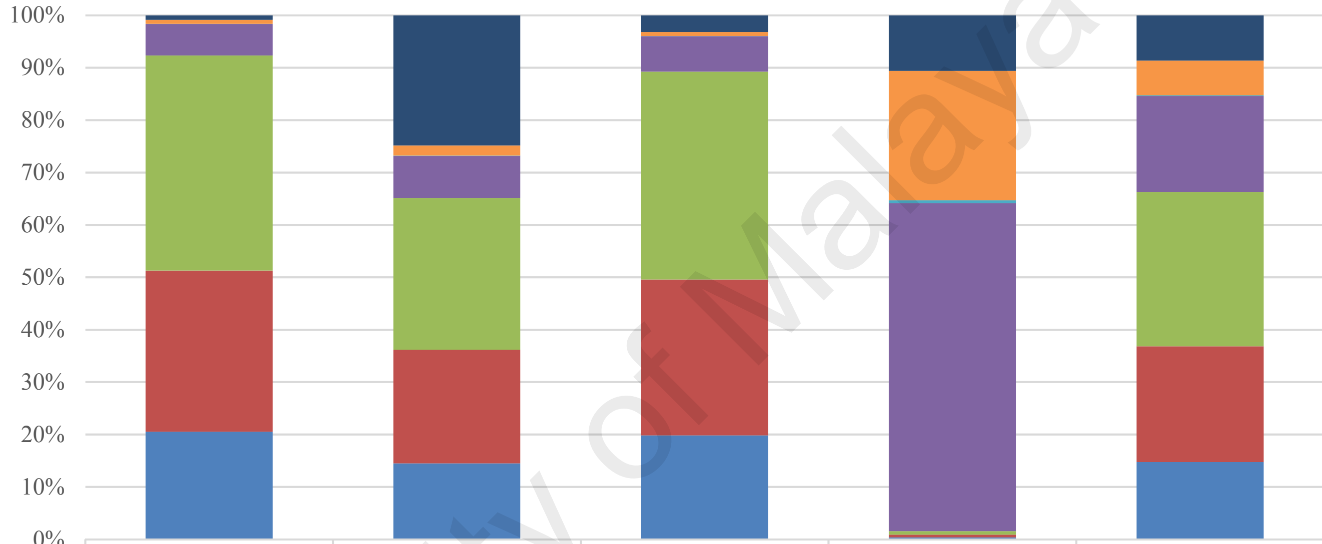
	kg SO2 eq Acidification	kg PO4 eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC 11 eq Ozone layer depletion (ODP)	kg 1,4 DB eq Human toxicity
End of Life	4.62E-01	1.92E+00	3.89E+02	4.05E-06	1.39E+02
Operations	1.10E+01	1.12E+00	2.41E+03	1.31E-07	2.36E+02
Construction	1.74E-02	5.04E-03	3.29E+00	2.03E-07	1.56E+00
Pre-use	3.23E+00	6.19E-01	8.25E+02	2.39E-05	2.94E+02
Maintenance 100 years	1.07.E+00	3.91.E-01	2.49.E+02	2.46.E-05	3.06.E+02
Maintenance - 75 years	7.65.E-01	2.79.E-01	1.75.E+02	1.76.E-05	2.08.E+02
Maintenance - 50 years	4.09.E-01	1.49.E-01	9.19.E+01	9.42.E-06	1.06.E+02

Figure 4.31: Sensitivity analysis of maintenance phase in comparison to other phases in different building lifespan

Figure 4.31 shows the comparison of the LCIA of different building lifespan for maintenance and also the comparison to other phases of the building. The impact on HT in maintenance shows significant increases and has exceeded the original analysis of the houses specifically compared to pre-use and EOL, contributed by the aluminium windows replacements. Although the impact on HT in operations phases shows similar result, the actual operation of the building based on the new lifespan will offset the increase LCIA in the maintenance phase. The result also shows the acidification in the maintenance phase is also surpassed to the impact in EOL for the 75 and 100 years. In conclusion, the changes of the building lifespan of the building has relatively high impact on the level of HT compared to other phases of the building especially to the pre-use and EOL phases.

4.9.3.2 Impacts in operation phase

The operation phase for PD with 50 years' lifespan has the highest impact on GWP and acidification with relatively high HT and eutrophication. The LCIA of the building were re-assessed with new lifespan similar to the maintenance phase. Figure 4.32 shows the LCIA of different building lifespan for operation and also the comparison to other phases of the building. The impact of HT in the operation phase in the 75 and 100 years' lifespan has exceeded the impact compared to the pre-use phase. In relation to other phases, only the operation phase in 100 years has exceeded in the ODP level in the construction phase and the eutrophication level in EOL. Other impacts in different building phases show relatively similar results pattern.



	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Human toxicity
End of Life	4.62.E-01	1.92.E+00	3.89.E+02	4.05.E-06	1.39.E+02
Maintenance	4.09.E-01	1.49.E-01	9.19.E+01	9.42.E-06	1.06.E+02
Construction	1.74.E-02	5.04.E-03	3.29.E+00	2.03.E-07	1.56.E+00
Pre-use	3.23.E+00	6.19.E-01	8.25.E+02	2.39.E-05	2.94.E+02
Operations - 100 years	2.20.E+01	2.24.E+00	4.83.E+03	2.62.E-07	4.72.E+02
Operations - 75 years	1.65.E+01	1.68.E+00	3.62.E+03	1.97.E-07	3.54.E+02
Operations - 50 years	1.10.E+01	1.12.E+00	2.41.E+03	1.31.E-07	2.36.E+02

Figure 4.32: Sensitivity analysis of operation phase in comparison to other phases in different building lifespan

4.9.3.3 Summary of findings

Changes in building lifespan will have an influence on the LCIA in two phases in the building life cycle namely maintenance and operation phases. Table 4.20 shows the sensitivity analysis of the total LCIA of PD based on different assumption of building lifespan. The results show that the building lifespan has a significant impact overall with a maximum increase of up to 77.11%. The level of acidification has the highest surge overall with 38.73% and 77.11%, followed by the level of GWP of 34.65% and 69.07% for 75 and 100 years' lifespan respectively, whereas eutrophication has the lowest surge overall.

4.10 Potential energy and LCIA reduction based on GBI criteria

The Green Building Index (GBI) is a building rating tool for green building in Malaysia, co-developed by Persatuan Arkitek Malaysia (PAM) – Malaysian Institute of Architects - and Association of Consulting Engineer Malaysia (ACEM). The GBI system evaluates six (6) main criteria including energy efficiency, indoor environment quality, sustainable site planning and management, material and resources, water efficiency and innovation. This research only focuses on the energy efficiency criteria, specifically to the advanced energy-efficiency performance (Figure 4.33) and renewable energy (Figure 4.36) based on the GBI residential new construction (RNC) version 3 (Green Building Index, 2013a). The characteristics of EEH will be used as a guidance due to its level of practicality to be implemented into conventional residential building's design in Malaysia. The characteristics then applied to GQ and PD to evaluate the energy efficiency performance and subsequently estimate the potential of environmental impact reduction.

Table 4.20: Sensitivity analysis of LCIA of different assumptions in building lifespan

Impact category		**Total (50 year's lifespan)**	**Total (75 year's lifespan)**	**Percentage increase**	**Total - 100 year's lifespan**	**Percentage increase**
Acidification	kg SO_2 eq	1.51.E+01	2.10.E+01	38.73%	2.68.E+01	77.11%
Eutrophication	kg PO_4 eq	3.82.E+00	4.51.E+00	18.09%	5.18.E+00	35.68%
Global warming (GWP100)	kg CO2 eq	3.72.E+03	5.01.E+03	34.65%	6.30.E+03	69.07%
Ozone layer depletion (ODP)	kg CFC 11 eq	3.77.E-05	4.59.E-05	21.99%	5.30.E-05	40.78%
Human toxicity	kg 1,4 DB eq	7.76.E+02	9.96.E+02	28.33%	1.21.E+03	56.08%

4.10.1 *Advanced energy efficiency performance*

The objective of this criteria is to reduce the energy consumption and to maintain the acceptable comfort level of the building (Green Building Index, 2013a). There are two (2) measurements required in this assessment, namely the overall thermal transfer value (OTTV) and U-value of the roof of the building. OTTV is an index to measure the thermal performance of a building in W/m^2 and the U-value of the roof is to measure the rate of transfer of heat across the materials in W/m^2K (Hong Kong Institute of Architects, 2012; Hui, 1997). The lower the values, the better the building performs and the higher points given in GBI assessment.

The evaluations of OTTV for GQ and PD are based on building energy intensity tool software namely Building Energy Intensity Tool (BEIT) version 1.1.0 by ACEM (ACEM, 2015) and the estimations of U-value of roof are based on the thermal resistance (m^2K/W) of building materials in roof construction. The BEIT software is developed for use specifically tailored to Malaysian climate and is one of the software approved by GBI for assessment of energy efficiency (Amirrudin & Chew, 2012).

ITEM	AREA OF ASSESSMENT	DETAIL POINTS	MAX POINTS	SCORES
DESIGN				
EE1	MINIMUM EE PERFORMANCE (MANDATORY COMPLIANCE)			
	Establish minimum Energy Efficiency (EE) performance to reduce energy consumption in buildings, thus reducing CO_2 emission to the atmosphere.		1	
	Meet the following minimum EE requirements as stipulated in MS1525 1) OTTV ≤ 50 W/m², ***AND*** 2) Lightweight Roof U-value ≤ 0.4 W/m²K Heavyweight Roof U-value ≤ 0.6 W/m²K	1		
EE2	ADVANCED EE PERFORMANCE			
	Establish EE Performance to reduce dependence on energy to keep indoor environment at satisfactory comfort level. Computed OTTV and Roof U-value to show lower dependence on energy to maintain indoor thermal comfort.			
	A) Landed			
	OTTV ≤ 46 W/m², ***OR***	1		
	OTTV ≤ 42 W/m², ***OR***	2		
	OTTV ≤ 38 W/m²	3		
	Lightweight Roof U-value ≤ 0.35 W/m²K / Heavyweight Roof U-value ≤ 0.50 W/m²K, ***OR***	1		
	Lightweight Roof U-value ≤ 0.30 W/m²K / Heavyweight Roof U-value ≤ 0.40 W/m²K, ***OR***	2		
	Lightweight Roof U-value ≤ 0.25 W/m²K / Heavyweight Roof U-value ≤ 0.30 W/m²K, ***OR***	3		
	Lightweight Roof U-value ≤ 0.20 W/m²K / Heavyweight Roof U-value ≤ 0.20 W/m²K, ***OR***	6		
	Lightweight Roof U-value ≤ 0.15 W/m²K / Heavyweight Roof U-value ≤ 0.15 W/m²K.	9		

Figure 4.33: Assessment of GBI residential new construction (RNC) version 3 for advanced energy efficiency performance (Green Building Index, 2013a)

4.10.1.1 OTTV

In GBI, the points given for OTTV for landed property are three (3) if the level is ≤ 38W/m^2, two (2) if ≤ 42W/m^2 and one (1) if ≤ 46W/m^2. The minimum requirement for OTTV level is ≤ 50W/m^2. The selected characteristics of EEH which were taken into consideration to reduce the OTTV level of GQ and PD are shown in Table 4.21. The buildings' relevant data such as the size, shape, the ratio of windows to wall including current and substitution specification were input in the BEIT software.

Table 4.21: Selected material upgrade applied in BEIT for OTTV calculation

Element	Unit	Base specification for GQ and PD			Proposed Specification from EEH		
		Materials	Value	Ref	Materials	Value	Ref
Building Envelope	U-Value (W/m^2K)	Clay brick, with internal and external plaster	5.64	(ACEM, 2015; Aktacir, Büyükalaca, & Yilmaz, 2010)	AAC Block, with internal skim coat and external plaster	1.07	(Aktacir et al., 2010; Pruteanu & Vasilache, 2013)
Windows	U-Value (W/m^2K)	Single Glazing Window	5.70	(ACEM, 2015)	Double Glazing	2.93	(ACEM, 2015)
Wall paint	Absorptivity (α)	Light colour	0.47	(HK Building Authority, 1995)	White semi-gloss paint	0.30	(HK Building Authority, 1995)

Figure 4.34 and Figure 4.35 shows the calculation of OTTV using the BEIT software. With current specification, OTTV level for both buildings was over 50W/m2 that did not meet the minimum requirement of GBI. With the proposed upgrades of the specification, the reduction of OTTV level for GQ and PD were significant with 60% and 35% respectively. The new OTTV level i.e. 21.98 W/m^2 and 35.90 W/m^2 for GQ and PD respectively are lower than the highest requirement of GBI, which is ≤ 38 W/m^2. The lower the OTTV means the building will have better performance in term of energy efficiency. The complete simulation of energy consumption and LCIA of the GQ and PD with the new OTTV will be conducted further in this chapter.

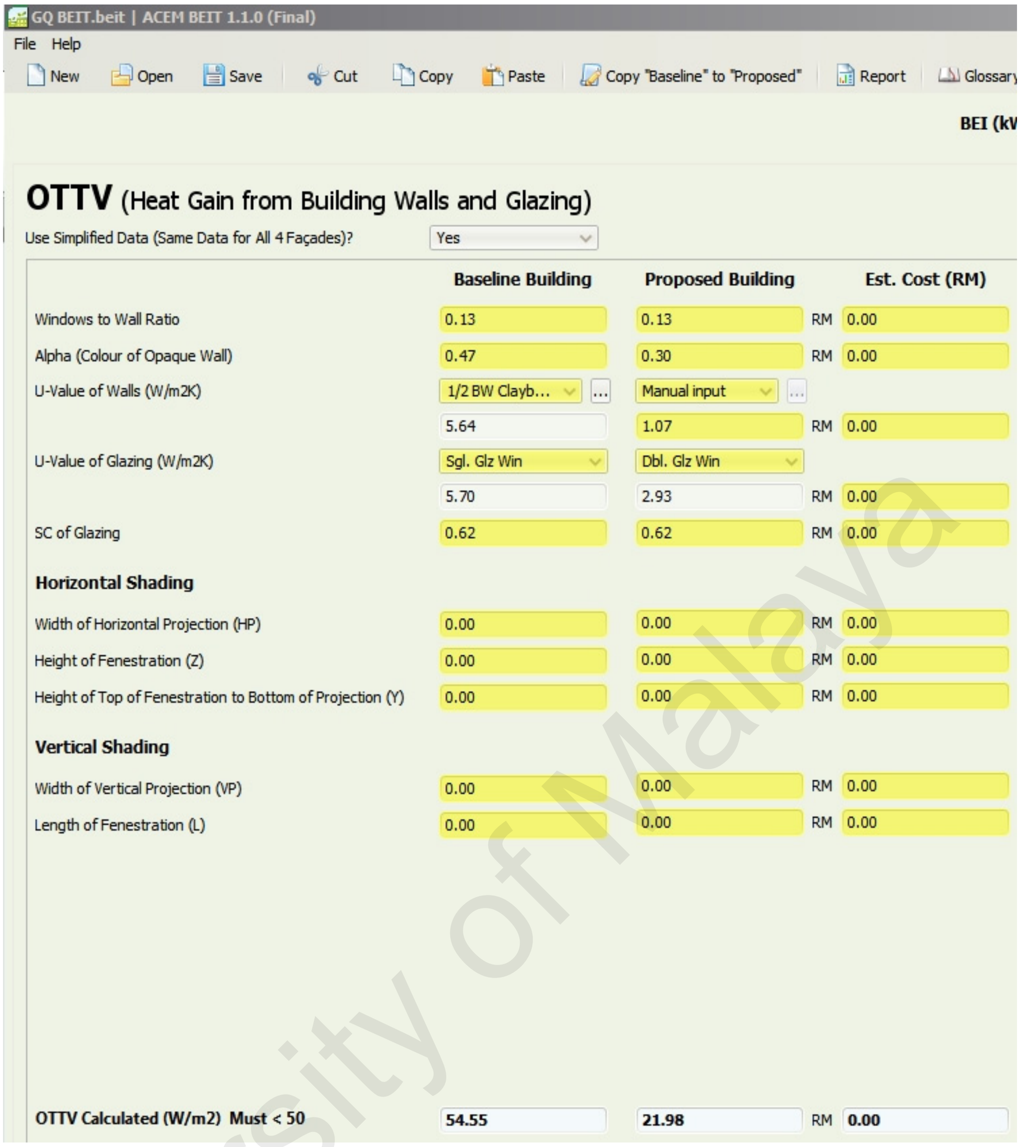


Figure 4.34: OTTV calculation for GQ using BEIT software

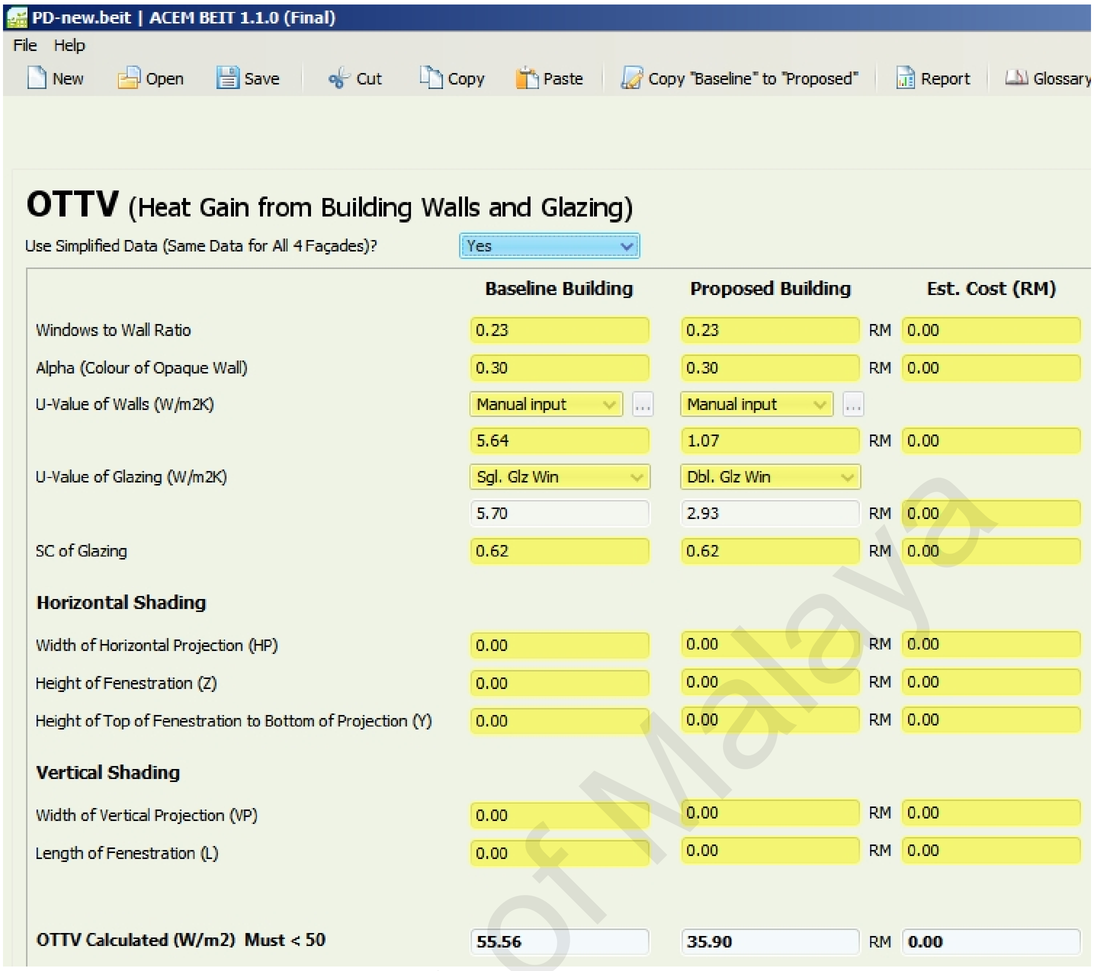


Figure 4.35: OTTV calculation for PD using BEIT software

4.10.1.2 Roof U-value

After the OTTV values are determined, the next GBI areas are the U-value of the roof. The minimum requirement of U-value is ≤ 0.4 W/m^{2}K and the maximum is ≤ 0.15 W/m^{2}K. Table 4.22 shows the calculation of roof U-value of GQ, PD, and EEH in W/m^{2}K. The U-value of EEH roof was estimated at 0.35 W/m^{2}K which exceeded the minimum requirement and scores additional one (1) point in advanced EE performance criteria.

Table 4.22: U-value of roof for GQ, PD, and EEH

Building	Material	Thermal Resistance (m^2K/W)	U-value (W/m^2K)	Ref
GQ	Steel Frame Roof	0.000		(Bradshaw, 2010)
	Concrete Tiles	0.007		(The Scottish Government, 2009)
	Fibre cement ceiling board 4.5mm thk	0.150		(UCO, 2012)
	Air	0.110		(Stoecklein, 2015)
	Total	**0.267**	**3.75**	
PD	Timber Frame Roof	0.000		(Bradshaw, 2010)
	Clay Tiles	0.010		(The Scottish Government, 2009)
	Fibre cement ceiling board 4.5mm thk	0.150		(UCO, 2012)
	Air	0.110		(Stoecklein, 2015)
	Total	**0.270**	**3.70**	
EEH	Steel Frame Roof	0.000		(Bradshaw, 2010)
	Steel roofing with building paper	0.010		(Stoecklein, 2015)
	50mm thk rockwool insulation	2.440		(Harimi, Harimi, Kurian, & Nurmin, 2005)
	Aluminium ceiling	0.275		(Kingspan, 2012)
	Air	0.110		(Stoecklein, 2015)
	Total	**2.835**	**0.35**	

The significant reduction of U-value of the roof was contributed by the rockwool insulation, which was not present in GQ and PD. The lower the U-value, the lower the heat transfer from roof to inside the house. The insulation also at the same time preventing cold air from escaping to the roof and thus can reduce the usage of air-conditioning.

4.10.2 *Renewable energy*

Item EE3 in the GBI encourage the usage of renewable energy in the building and the points as shown in Figure 4.36 (Green Building Index, 2013a). The installation of solar PV to GQ and PD can reduce the dependency towards electricity from the grid. The GBI points were given based on the capacity of the solar PV installed to the house. The solar PV installed in EEH has the total capacity of 4.8kWp that exceeded the maximum criteria set in GBI (Boswell & Bacon, 2009).

The total electricity generated were assumed similar to the electricity generated in EEH with forty (40) 120-watt polycrystalline solar panels on the roof. The final energy reduction is expected to be 58.5% and 41.3% respectively which can reduce the total environmental impact of the buildings as shown in Table 4.23. Subsequently, the impact of electricity equivalent generated from Malaysian mix generation (290,746.98 kWh) was compared to the manufacture and installation of 40m^2 of solar panel including a replacement after lifespan of 30 years and disposal by using CML 2001.

EE3	RENEWABLE ENERGY		
	Encourage use of renewable energy systems to offset energy cost and promote green energy use.		5
	A) Landed		
	Where 1 kWp is generated by renewable energy (PV or equivalent), ***OR***	1	
	Where 2 kWp or 40% of building energy consumption (whichever is the greater) is generated by renewable energy (PV or equivalent), ***OR***	2	
	Where 3 kWp or 60% of building energy consumption (whichever is the greater) is generated by renewable energy (PV or equivalent), ***OR***	3	
	Where 4 kWp or 80% of building energy consumption (whichever is the greater) is generated by renewable energy (PV or equivalent), ***OR***	4	
	Where 4 kWp or 100% of building energy consumption (whichever is the greater) is generated by renewable energy (PV or equivalent).	5	

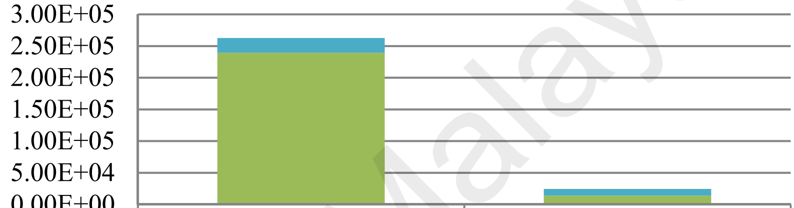
Figure 4.36: Assessment of GBI residential new construction (RNC) version 3 for renewable energy (Green Building Index, 2013a)

Table 4.23: Energy Consumptions Analysis for Three Case Studies and Potential Savings by Solar PV

Building	Gross Floor Area (m^2)	Energy Consumption for 50 years (kWh)	Energy Consumption per GFA (kWh/m^2)	Potential Solar Generation for 50 years per GFA* (kWh/m^2)	Net Energy Consumption from Grid (kWh/m^2)	% of Potential Energy Savings from PV
GQ	218	496,831.05	2,279.04	1,333.70	945.34	58.5%
PD	246	725,644.95	2,949.78	1,181.90	1,767.88	40.1%
EEH	232	431,350.00	1,859.21	1,253.22	605.99	67.4%

*Data as per EEH Solar Generation

Figure 4.37 shows the comparison results between the amount of electricity from grid equivalent to generated from the solar panel and manufacturing, installation and disposal of solar panel for 80m^2. Electricity from the grid has the highest impact overall excluding ODP, which is lower than a solar panel. The high ODP in solar panel is because of the uses of chemical such as tetrafluoroethylene at 27.7% (9.41E-04 kg CFC-11 eq) and trichloromethane at 25.1% (8.55E-04 kg CFC-11 eq) of overall ODP used in the manufacturing process of PV panel.



	Electricity Generated	Solar Panel 40m2
Human toxicity kg 1,4-DB eq	2.33E+04	1.05E+04
Ozone layer depletion (ODP) kg CFC-11 eq	1.29E-05	3.40E-03
Global warming (GWP100) kg CO2 eq	2.38E+05	1.37E+04
Eutrophication kg PO4 eq	1.10E+02	2.60E+01
Acidification kg SO2 eq	1.08E+03	5.21E+01

Figure 4.37: Comparison of LCIA of electricity mix generation equivalent for solar generated and manufacturing, installation and disposal of solar panels by using CML 2001

4.10.3 *Air-conditioning setting*

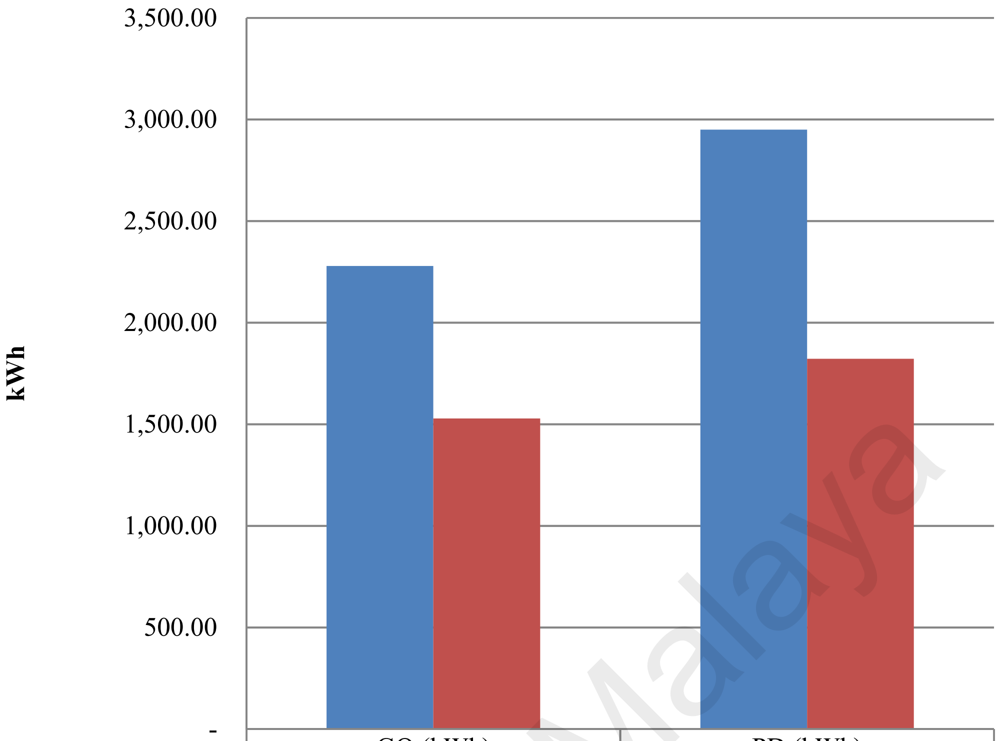
The air conditioning has been identified as the largest energy consumer in the building based on results for energy consumptions for all building. The simulation was done for GQ and PD previously were conducted based on the average temperature setting of 20.8^o Celcius for residential building by Kubota, Jeong, Toe, & Ossen (2011). Currently, there are no emphasize on the temperature setting for air-conditioning in the GBI. However recent research suggested that the comfort level for Malaysian is at 24^o

Celcius and is being applied to all government office buildings in Malaysia (The Star, 2011). Similarly, the temperature setting in EEH is also set at 24° Celcius.

Thus to estimate the potential energy savings of GQ and PD, the buildings were re-simulated with the temperature setting at 24° Celcius for 8 hours operations per day. The data collected are then tabulated in Table 4.24. The result showed that the reduction of temperature setting would reduce the overall energy consumption of 50 years per GFA by 750.73 kWh (33%) and 1,127.28 kWh (38%) for GQ and PD respectively.

Table 4.24: Energy consumptions analysis for GQ and PD with potential energy savings by changing temperature setting

Building	Annual Energy Consumption (kWh)							Gross Floor Area (GFA) (m2)	Annual Energy Consumption per GFA (kWh/m2)	Energy Consumption for 50 years (kWh)	Total Energy Consumption per GFA (kWh)	Remark
	Lighting		Electrical Equipment		Air conditioning system		Total					
GQ	1,801.90	18.13%	4,011.84	40.37%	4,122.88	41.49%	9,936.62	218	45.58	496,831.05	2,279.04	20.8 ^{o}C
	1,801.90	27.04%	4,011.84	60.21%	849.68	12.75%	6,663.42		30.57	333,171.05	1,528.31	24 ^{o}C
PD	2,382.85	16.42%	5,305.32	36.56%	6,824.73	47.03%	14,512.90	246	59.00	725,644.95	2,949.78	20.8 ^{o}C
	2,382.85	26.58%	5,305.32	59.19%	1,275.55	14.23%	8,963.72		36.44	448,185.95	1,821.89	24 ^{o}C



	GQ (kWh)	PD (kWh)
Set at 20.8 celcius	2,279.04	2,949.78
Reset to 24 celcius	1,528.31	1,821.89

Figure 4.38: Energy consumptions analysis for GQ and PD with potential energy savings by changing temperature setting

4.10.4 *Results on potential energy reduction*

The re-simulation were done by using Openstudio to estimate the potential energy reduction of every change made to the GQ and PD with new specification as mentioned previously as follows:

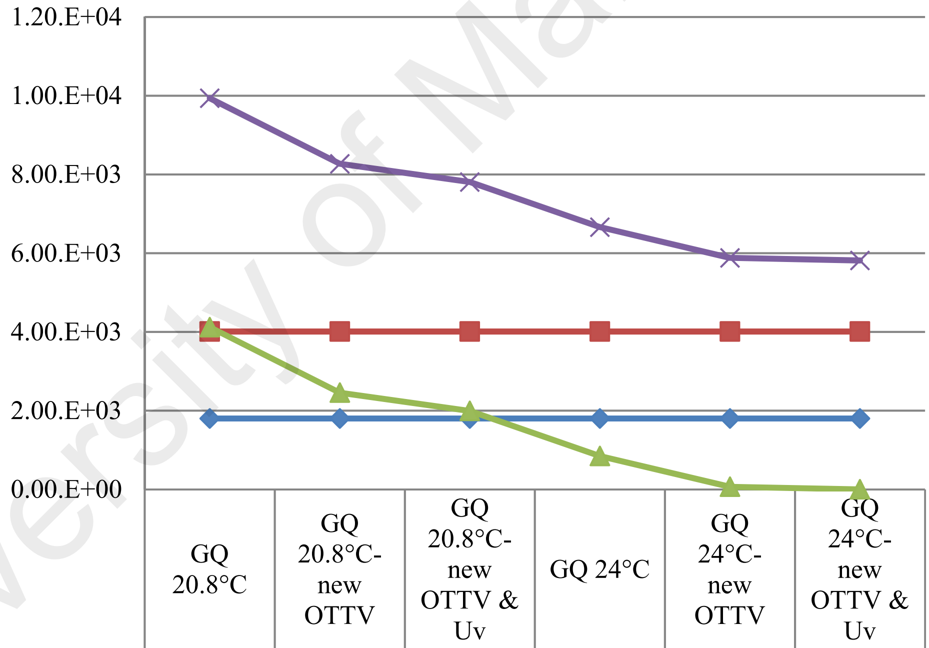
a) New OTTV value with temperature of 20.8° Celcius

b) New OTTV and roof U-value with temperature of 20.8° Celcius

c) New OTTV value with temperature of 24° Celcius

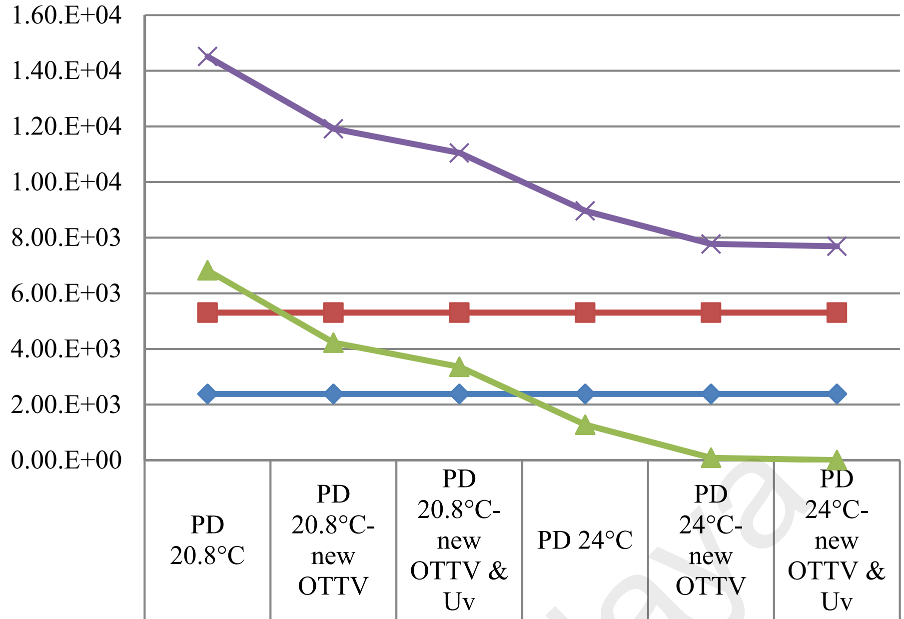
d) New roof U-value with temperature of 24° Celcius

Figure 4.39 and Figure 4.40 shows the result of the simulation. The new specification only reduced the energy consumed by the air-conditioning and does not affect lighting and electrical equipment. Overall, the new OTTV and roof U-value of the house have reduced the annual energy consumption of 21.41% and 41.47% for GQ with the air-conditioning setting of 20.8° Celcius and 24° Celcius respectively. The PD has reduced the annual energy consumption of 23.88% and 47.00% with the air-conditioning setting of 20.8° Celcius and 24° Celcius respectively. In conclusion, if the occupants in the upgraded GQ and PD were comfortable with a temperature of 24° Celsius, they could avoid the air conditioning system completely.



	GQ 20.8°C	GQ 20.8°C-new OTTV	GQ 20.8°C-new OTTV & Uv	GQ 24°C	GQ 24°C-new OTTV	GQ 24°C-new OTTV & Uv
Lighting	1.80.E+03	1.80.E+03	1.80.E+03	1.80.E+03	1.80.E+03	1.80.E+03
Electrical equipments	4.01.E+03	4.01.E+03	4.01.E+03	4.01.E+03	4.01.E+03	4.01.E+03
Air-conditioning	4.12.E+03	2.46.E+03	2.00.E+03	8.50.E+02	6.80.E+01	2.64.E+00
TOTAL	9.94.E+03	8.27.E+03	7.81.E+03	6.66.E+03	5.88.E+03	5.82.E+03

Figure 4.39: Potential annual energy reduction of GQ with new OTTV, roof value and temperature setting



	PD 20.8°C	PD 20.8°C-new OTTV	PD 20.8°C-new OTTV & Uv	PD 24°C	PD 24°C-new OTTV	PD 24°C-new OTTV & Uv
Lighting	2.38.E+03	2.38.E+03	2.38.E+03	2.38.E+03	2.38.E+03	2.38.E+03
Electrical equipments	5.31.E+03	5.31.E+03	5.31.E+03	5.31.E+03	5.31.E+03	5.31.E+03
Air-conditioning	6.82.E+03	4.23.E+03	3.36.E+03	1.28.E+03	8.74.E+01	3.52.E+00
TOTAL	1.45.E+04	1.19.E+04	1.10.E+04	8.96.E+03	7.78.E+03	7.69.E+03

Figure 4.40: Potential annual energy reduction of PD with new OTTV, roof value and temperature setting

Table 4.25: Potential energy reduction for GQ and PD with new OTTV, roof value, temperature setting and potential solar PV generation

	Annual Energy Consumption (kWh)	**Energy Consumption for 50 years (kWh)**	**Gross Floor Area (m^2)**	**Energy Consumption per GFA (kWh/m^2)**	**Potential Solar Generation for 50 years per GFA* (kWh/m^2)**	**Net Energy Consumption from Grid (kWh/m^2)**
GQ	5,816.38	290,819.03	218	1,334.03	1,333.70	0.33
PD	7,691.69	384,584.43	246	1,563.35	1,181.90	381.45

*Data as per EEH Solar Generation

Table 4.25 shows the new estimated energy consumption of the GQ and PD. GQ has the highest energy reduction of 99.99% in comparison to the original house due to its lower air-conditioning usage and the renewable energy generated by the solar PV. PD also has significant energy reduction by 87.07% in comparison to the original house.

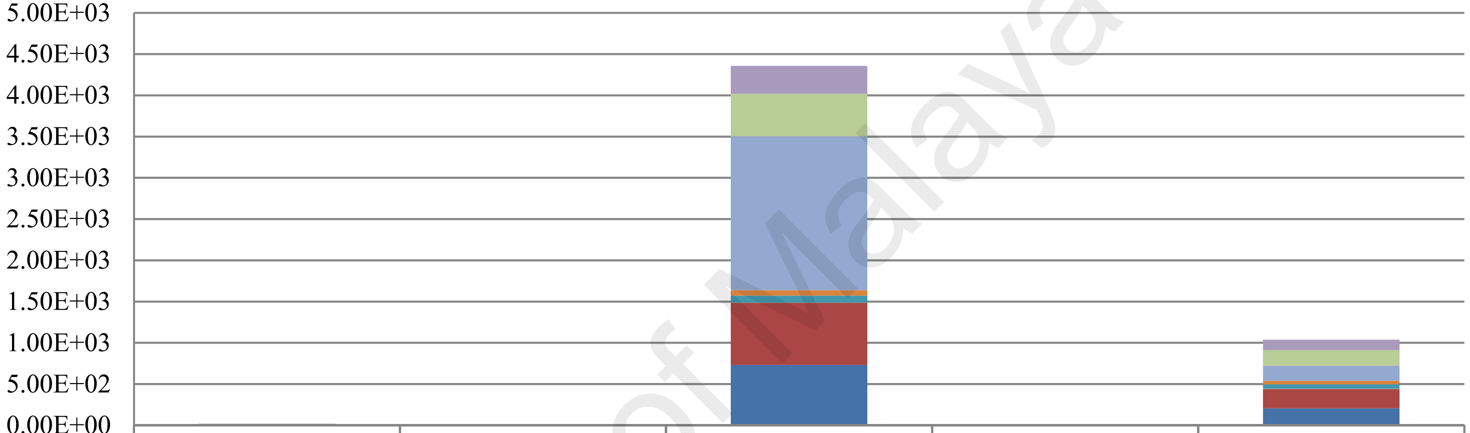
4.10.5 *Results on potential LCIA reduction*

The GQ and PD with the new OTTV and roof U-value were re-assessed in SimaPro. The Solar PV installation in the pre-use phase and electricity generation potential were included in the LCA. The results were then compared to the original LCIA. Table 4.26, Figure 4.41 and Figure 4.42 shows the potential of LCIA reduction of these two residential buildings. The results showed that the overall LCIA had reduced significantly for all impact categories excluding the ODP as shown in Table 4.26. The increasing impact in ODP was primarily in pre-use phase due to the substitution of clay bricks to AAC block and also additional materials included in the buildings specifically the Rockwool insulation in the roof and also solar PV panel.

The LCIA in pre-use phase has increased due to the additional materials added as mentioned previously. Other phases showed a reduction in LCIA excluding the construction phase that remains the same. The operation phase shows significant impact reduction due to the decrease in energy consumption. The reduction of LCIA in maintenance was due to changes of the roof coverings from concrete and clay roof tiles to steel coverings in GQ and PD respectively. In EOL phase, the LCIA of disposal of AAC blocks was marginally lower compared to clay bricks. The LCIA of steel roof coverings also was slightly lower than concrete and clay roof tiles in GQ and PD respectively. In conclusion, the replacement of materials to reduce the OTTV and roof U-value according to GBI's criteria with the air-conditioning temperature setting to 24^{o} Celsius could reduce the energy and LCIA of the residential buildings in Malaysia.

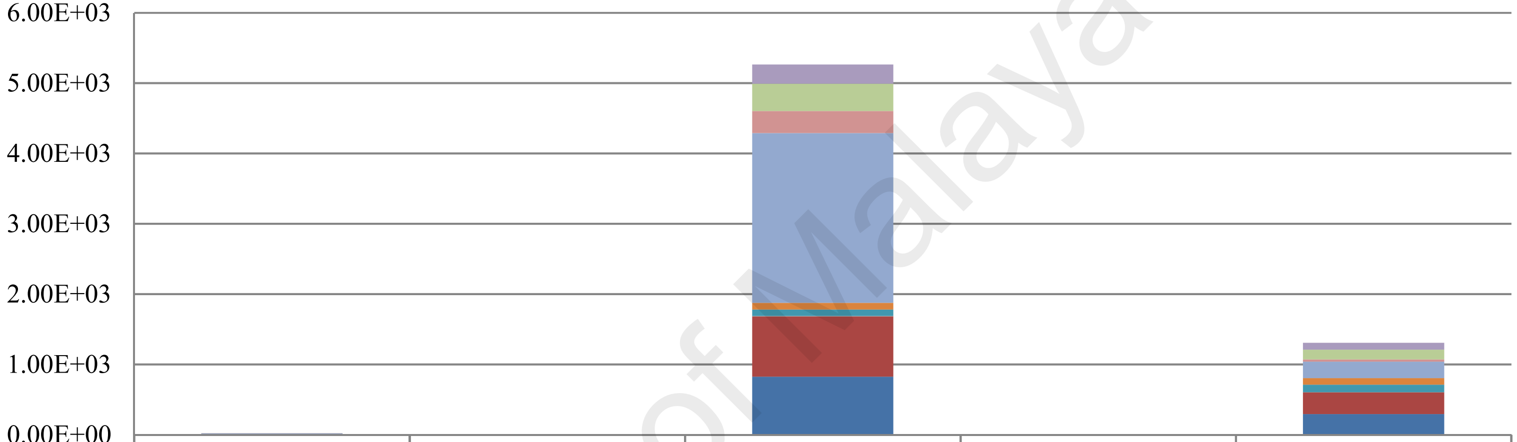
Table 4.26: Comparison of LCIA of original and updated GQ and PD from cradle-to-grave using CML 2001

Impact Categories	**Unit**	**GQ**	**Updated GQ**	**Reduction**	**PD**	**Updated PD**	**Reduction**
Acidification	kg SO_2 eq	1.22.E+01	3.67.E+00	69.82%	1.51.E+01	5.86.E+00	61.23%
Eutrophication	kg PO_4-eq	4.27.E+00	2.54.E+00	40.43%	3.82.E+00	2.35.E+00	38.42%
Global warming (GWP100)	kg CO_2 eq	3.19.E+03	1.16.E+03	63.65%	3.72.E+03	1.54.E+03	58.65%
Ozone layer depletion (ODP)	kg CFC-11 eq	3.70.E-05	4.01.E-05	-8.32%	3.77.E-05	3.83.E-05	-1.77%
Human toxicity	kg 1,4-DB eq	6.32.E+02	4.06.E+02	35.80%	7.76.E+02	5.31.E+02	31.55%



	kg SO2 eq Acidification	kg PO4-eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
END-OF-LIFE Updated GQ	3.52E-01	1.76E+00	3.39E+02	3.30E-06	1.26E+02
END-OF-LIFE GQ	4.85E-01	2.66E+00	5.14E+02	4.52E-06	1.90E+02
OPERATION Updated GQ	1.23E-03	1.25E-04	2.70E-01	1.47E-11	2.64E-02
OPERATION GQ	8.49E+00	8.65E-01	1.87E+03	1.01E-07	1.82E+02
MAINTENANCE Updated GQ	3.93E-01	1.37E-01	6.67E+01	7.82E-06	4.39E+01
MAINTENANCE GQ	4.30E-01	1.42E-01	8.04E+01	8.52E-06	5.23E+01
CONSTRUCTION Updated GQ	2.51E-02	7.29E-03	4.70E+00	2.92E-07	2.32E+00
CONSTRUCTION GQ	2.51E-02	7.29E-03	4.70E+00	2.92E-07	2.32E+00
PRE-USE Updated GQ	2.90E+00	6.45E-01	7.51E+02	2.87E-05	2.33E+02
PRE-USE GQ	2.73E+00	5.96E-01	7.30E+02	2.36E-05	2.06E+02

Figure 4.41: LCIA of GQ and updated GQ from cradle-to-grave using CML 2001



	kg SO2 eq Acidification	kg PO4-eq Eutrophication	kg CO2 eq Global warming (GWP100)	kg CFC-11 eq Ozone layer depletion (ODP)	kg 1,4-DB eq Human toxicity
END-OF-LIFE Updated PD	3.68E-01	1.33E+00	2.73E+02	3.25E-06	9.76E+01
END-OF-LIFE PD	4.62E-01	1.92E+00	3.89E+02	4.05E-06	1.39E+02
OPERATION Updated PD	1.42E+00	1.45E-01	3.12E+02	1.70E-08	3.05E+01
OPERATION PD	1.10E+01	1.12E+00	2.41E+03	1.31E-07	2.36E+02
MAINTENANCE Updated PD	5.29E-01	1.73E-01	9.36E+01	7.43E-06	9.19E+01
MAINTENANCE PD	4.09E-01	1.49E-01	9.19E+01	9.42E-06	1.06E+02
CONSTRUCTION Updated PD	1.74E-02	5.04E-03	3.29E+00	2.03E-07	1.56E+00
CONSTRUCTION PD	1.74E-02	5.04E-03	3.29E+00	2.03E-07	1.56E+00
PRE-USE Updated PD	3.52E+00	6.94E-01	8.57E+02	2.74E-05	3.10E+02
PRE-USE PD	3.23E+00	6.19E-01	8.25E+02	2.39E-05	2.94E+02

Figure 4.42: LCIA of PD and updated PD from cradle-to-grave using CML 2001

4.11 Potential carbon emission reduction for residential building in Malaysia

Based on the results shown in Table 4.25, the potential reduction of annual energy consumed by building GQ and PD are estimated at 99.99% and 87.07% respectively. Therefore the average or reduction is estimated at 93.53%. The estimated of reduction of carbon emission is based on the following assumptions:

- The average energy reduction is estimated at 93.53% based on the results in Table 4.25.
- The estimation is based on the year 2013 due to the limitation of data on the CO_2 emission.
- The number of existing residential building as at quarter 4 in 2013 is 4,661,335 units based on Residential Property Stock Report by National Property Information Centre (NAPIC, 2013).
- Only landed residential buildings are considered (2,679,480 units) in the equation excluding the low-cost houses which are built with lower cost limitation which may overlook the sustainable features.
- Total residential units estimated to own air-conditioner is at 65%, based on the findings by Kubota et al. (Kubota et al., 2011).
- Total energy consumed by residential buildings in 2013 is 26,288 GWh, and the total of all sectors is 123,076 GWh based on the National Energy Balance 2013 by Suruhanjaya Tenaga (Suruhanjaya Tenaga Malaysia, 2013b).
- Total carbon emission is estimated using a grid emission factor of 0.684 ton CO_2 per 1 GWh of energy as suggested by (Zaid, Myeda, Mahyuddin, & Sulaiman, 2015).

- In 2005, the Malaysian CO_2 emission was 152.78 Mt of CO_2 and emission intensity per GDP (kg CO_2/GDP) estimated in 2005 is 1.08 based on a report by International Energy Agency (IEA, 2016a).

The estimated reduction was calculated based on the following equation:

$$CO2_R = E\,\frac{H1}{H2}\,A\,G\,(x_R) \tag{1}$$

Where;

$CO2_R$: Reduction of CO_2

E: Total energy consumed by residential buildings in 2013

H1: Number of landed houses considered

H2: Total number of houses in 2013

A: Percentage of houses with air-conditioner

G: Grid emission factor

x_R: Average estimated energy reduction

Based on the equation, the potential reduction of CO_2 is estimated at 6,283.74 kton CO_2 or 6.28 Mt of CO_2. The latest CO_2 emission is only available up to 2013 with the total emission is 207.25 Mt of CO_2, and the GDP is 207.95 billion USD, which translated to 1.00 kg CO_2/GDP (IEA, 2016b). The potential CO_2 emission with improvement is estimated at 200.97 Mt of CO_2, which is translated to 0.9664 kg CO_2/GDP or 3.36% reduction in carbon emission intensity.

CHAPTER 5 : CONCLUSIONS

5.1 Introduction

In this chapter, the findings in the previous chapter are summarised and correlate to the aims and objectives of this research. This research was conducted to evaluate and establish a benchmark of the conventional residential building in Malaysia in term of its environmental impact for the whole life cycle using LCA. Moreover, the environmental impact of an energy efficient house was also being established and compared to the conventional residential buildings. This research also managed to identify critical areas in the system and at the same time proposed the potential for improvement with reference to the selected green building criteria. Furthermore, the estimated potential of carbon emission reduction is presented in line with the sustainable development and green technology initiatives by Malaysian Government as discussed in the previous chapter. Finally, suggestions for future research are presented. Therefore, the findings from this research has successfully achieved the set objectives established in the first chapter.

5.2 LCIA of residential buildings in Malaysia

The first objective was to evaluate and establish a benchmark of the environmental impact of the whole life cycle of conventional Malaysian residential building using LCA. Two (2) residential buildings with different specifications have been evaluated. The first and second buildings were constructed based on the Public Works Department and public developer's specification respectively. The second objective was to evaluate the energy efficient house and then compared to the conventional residential building assessed earlier.

The results showed that there are similarities between the buildings in Malaysia and in other countries where the operation phase has the highest environmental impact specifically GWP and acidification levels in comparison to other studies due to its duration. The sensitivity analysis were conducted to test the magnitude of variation if the duration is extended to 75 and 100 years instead of 50 years. The results showed that the operation phase exceeds in all environmental impacts excluding the ODP which. was dominated by the pre-use where the building materials consist of clay bricks in GQ and PD and solar panel in EEH. The level of eutrophication is the highest in the EOL phase, include the disposal of clay and cement based products, primarily clay bricks in GQ and PD and the AAC concrete block in EEH, followed by clay roof tiles, ceramic tiles, baseplaster, and screed. Similar to other research, the construction phase has the lowest impact overall, followed by the maintenance phase.

The results were then compared to other published data for validation. The results were compared to the 4-storey conventional and IBS flats from cradle-to-gate, located in Johor, Malaysia. Additional comparisons were made from cradle-to-grave to two other semi-detached house, located in the UK and Spain. Only GWP was compared to the flat and the terrace, semi-detached, and detached house in the UK as it is the only data available. The environmental impact data available for the house in Spain, are more extensive which includes the GWP, acidification, ODP, and HT.

All case studies were higher in comparison to the flats which may have a different specification of building materials and the quantity per m^2 of materials were varied. Moreover, most of the elements in the flat are shared between multiple units such as roof, wall, floor and ceiling. The comparison of GWP for cradle-to-grave of the case studies to the UK and Spain houses were relatively comparable. Similar results showed that the operation/use phase of the houses contributed the largest GWP and acidification. The results also showed that the pre-use phase is responsible for the largest impact on ODP and HT while the EOL has the largest impact on eutrophication.

Overall, the EEH has the lowest impact of GWP, acidification, ODP and HT in comparison to GQ and PD including the houses in the UK and Spain.

5.3 Potential energy and LCIA reduction of residential buildings in Malaysia

The third objective is to quantify the potential environmental impact reduction and subsequently estimate the carbon emission reduction potential. The GBI criteria and practical specification in EEH were used to estimate the potential energy reduction for GQ and PD. The criteria that are being applied are the reduction of OTTV value and roof U-value. The EEH specification was used to replace the original specification in GQ and PD, which includes replacement of materials in the wall, windows, wall paint, and roof. The installation of solar PV was included with the potential solar generation based on data by EEH. Additional adjustment on the air-conditioning was made by increasing the temperature setting to 24^{o} Celcius as recommended by previous research. The results show that significant reduction in energy consumption of 99.99% and 87.07% of GQ and PD respectively. The findings highlighted that the changes in materials and the addition of insulation and solar PV, and re-setting the temperature of the air-conditioning could tremendously reduce the total energy consumption.

The new specifications of GQ and PD were re-assessed in SimaPro. The results show that most impact has reduced significantly especially in acidification (61 - 70%) and GWP (59 - 64%) reflected from the reduction of energy usage. Eutrophication impact has also reduced relatively high with 38 - 40% and HT with 32 - 36%. On the contrary, ODP level has increased by 2 - 8%, primarily in the pre-use phase where the inclusion of new materials namely AAC blocks, insulation, and the solar PV panel. Based on the improvement, it is estimated that the residential building in Malaysia has the potential to reduce 6.28 Mt of CO_2 or 3.36% reduction in carbon emission intensity per GDP, in line with the pledged by the Prime Minister of Malaysia for 40% reduction by the year 2020.

5.4 Overall conclusions

In general, conventional residential building in Malaysia has a higher environmental impact in comparison to energy efficient buildings primarily to energy consumption throughout the operation phase. The replacement and addition of materials according to the GBI and EEH criteria can reduce most of the environmental impact significantly. The slight increase in ODP level may be outweighed by the larger potential of reduction in other impact categories. The results also showed that the introduction of the GBI to the building industry did have an impact on the reduction of energy and environmental reduction in line with the policy objectives, and the policy pillars of energy and environment of the Malaysian National Green Technology Policy. The Malaysian electricity mix which predominantly from fossil fuel responsible for the high GWP, HT and eutrophication and the increase of renewable energy can improve the environmental impact in Malaysia especially the carbon emission.

5.5 Recommendation for future research

Recommendation for future research may include detail cradle-to-grave LCA to a different type of residential and commercial buildings and established an environmental impact database for building materials in Malaysia. Future researcher also may consider the potential increase of renewable energy electricity generation in Malaysia for the next 50 years, and how the improvement can influence the overall buildings environmental impact compare to the trade-off of energy efficiency building materials. Another area that needs further research is the comparison of Process Based, Economic Input-Output (EIO-LCA) and Hybrid LCA for buildings in Malaysia with different environmental impact indicators. Other potential area are the relationship of LCA and life cycle costing and Social-LCA to buildings in Malaysia to measure the potential of LCIA reduction environmentally, economically and socially.

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